Drying Characteristics of Saskatoon Berries under Microwave and Combined Microwave-Convection Heating

A Thesis Submitted to the
College of Graduate Studies and Research
in Fulfillment of the Requirements for the
Degree of Master of Science
in the Department of Agricultural and
Bioresource Engineering,
University of Saskatchewan, Saskatoon.

Thesis Submitted By

Lakshminarayana Reddy

PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a postgraduate degree from the University of Saskatchewan, I agree that the Libraries of this University may make it freely available for inspection. I further agree that permission for copying of this thesis in any manner, in whole or in part, for scholarly purposes may be granted by the professor or professors who supervised my thesis work or, in their absence, by the Head of the Department or Dean of the College in which my thesis work was done. It is understood that any copying or publication or use of this thesis or parts thereof for financial gain shall not be allowed without my written permission. It is also understood that due recognition shall be given to me and to the University of Saskatchewan in any scholarly use which may be made of any material in my thesis.

Requests for permission to copy or to make other use of material in this thesis in whole or in part should be addressed to:

Head of the Department
Department of Agricultural and Bioresource Engineering
57 Campus Drive
University of Saskatchewan
Saskatoon, Saskatchewan S7N5A9

DEDICATION

Dedicated to my lovable Amma (mother)

ACKNOWLEDGEMENT

I thank my parents, brothers and all family members for their support.

My thanks to all, who inspired and helped me in fulfilling the thought of pursuing M. Sc. education abroad. Mr. Ramachandra, Dr. Ranganna and dearest friends Arun and Nagaraj for their moral support.

My special thanks to my supervisor Dr. Meda, who has been a mentor and has supported right through the M. Sc. program.

I thank Dr. Panigrahi for his financial assistance and his constant support.

Mr. Wayne Morley was instrumental in technically guiding in the electronics assembly and development of the microwave drying system. My special thanks to him.

I thank Mrs. Grace Whittington, Riverbend plantations, for providing us with saskatoon berries for the research work.

My thanks to all the graduate advisory committee members who have constantly helped in framing the research study.

Thanks to Mr. Bill Crerar and Mr. Louis Roth for helping in instrumentation work.

Finally, thanks to all my co-graduate students and Department of Agricultural and Bioresource Engineering.

Special thanks to all the members of saskatoon kannada community for making me feel this place the same as home.

Thanks to NSERC and Department of Agricultural and Bioresource for funding.

ABSTRACT

The study on dehydration of frozen saskatoon berries and the need for dried fruits has been strategically identified in the prairies. Our motivation was to find a suitable method for dehydration in order to extend saskatoon berry shelf life for preservation. Microwave, convection and microwave-convection combination drying processes were identified to finish-dry saskatoon berries after osmotic dehydration using sucrose and high fructose corn syrup (HFCS) sugar solutions. Osmotic dehydration removes moisture in small quantities and also introduces solutes into the fruit that acts as a preservative and also reduces the total drying time.

Due to the very short harvesting season of saskatoon berries, an accelerated process like microwave combination drying can bring down the moisture to safe storage level, immediately after harvest. Untreated and osmotically dehydrated berries were subjected to convection (control), microwave and microwave-convection combination drying conditions at different product drying temperatures (60, 70 and 80^{0}C) until final moisture content was 25% dry basis. A laboratory-scale microwave combination dryer was developed, built with temperature and moisture loss data acquisition systems using LabView 6i software. Thin-layer cross flow dryer was used for convection-only drying and for comparison.

Drying kinetics of the drying processes were studied and curve fitting with five empirical equations including Page equation, was carried to determine drying constant, R^2 and standard error values. The microwave-combination drying method proved to be the best for drying saskatoon berries. Dehydrated product quality analysis by means of color changes, rehydration ratio measurements and observed structural changes with scanning electron microscope technique were the factors in drying method selection for saskatoon berries.

This research was instrumental in the modification and development of a novel drying system for high-moisture agricultural materials. Microwave-convection combination drying at 70^{o}C, yields good results with higher drying rates and better end-product quality.

TABLE OF CONTENTS

PERMISSION TO USE ---------- i
DEDICATION ---------- ii
ACKNOWLEDGEMENT ---------- iii
ABSTRACT ---------- iv
TABLE OF CONTENTS ---------- vi
LIST OF TABLES ---------- x
LIST OF FIGURES ---------- xi
LIST OF SYMBOLS AND GLOSSARY ---------- xv
CHAPTER I - INTRODUCTION ---------- 1
1.1 Introduction ---------- 1
1.2 Objectives ---------- 3
CHAPTER II – LITERATURE REVIEW ---------- 4
2.1. Saskatoon Berries ---------- 4
2.1.1. Fruit Composition ---------- 6
2.1.2. Production and Post-harvest Technology ---------- 8
2.1.3. Freezing vs. Drying ---------- 11
2.2 Fruit Pretreatment ---------- 12
2.2.1. Chemical Pretreatment ---------- 13
2.2.2 Osmotic Dehydration ---------- 13
2.3 Fruit Preservation Techniques ---------- 16
2.3.1 Dehydration / Drying ---------- 16
2.3.2 Introduction to Agri-Food Material Drying ---------- 17
2.4 Electrical Properties of Foods ---------- 18
2.4.1 General Principles – Dielectric Properties ---------- 19
2.4.2 Influence of Moisture Content ---------- 21
2.4.3 Influence of Density ---------- 22
2.4.4 Influence of Temperature ---------- 22
2.4.5 Importance of Dielectric Properties ---------- 22

2.4.6 Dielectric Measuring Systems ---------- 23
2.5 Drying Systems ---------- 24
2.5.1 Hot-air Drying ---------- 25
2.5.2 Cabinet Dryers ---------- 25
2.5.3 Tunnel Dryers ---------- 25
2.5.4 Microwave Heating ---------- 26
2.5.5 Infrared Drying ---------- 28
2.5.6 Microwave-Hot-Air Combination Drying ---------- 29
2.5.7 Microwave-Infrared Drying ---------- 30
2.5.8 Microwave-Vacuum Drying ---------- 30
2.5.9 Freeze Drying ---------- 30
2.6 End-product Quality Analysis ---------- 31
2.7 Berry Drying Studies ---------- 31
2.8 Summary of Chapter II ---------- 33
CHAPTER III – MATERIALS AND METHODS ---------- 34
3.1. Experimental Plan and Procedure ---------- 34
3.1.1 Chemical Pretreatment ---------- 35
3.1.2 Osmotic Dehydration ---------- 35
3.1.3 Saskatoon Berry Drying ---------- 36
3.1.4 Microwave and Microwave-Convection Drying ---------- 37
3.1.5 Convection Drying ---------- 37
3.2 Analytical Procedures ---------- 38
3.2.1 Berry Sample Preparation ---------- 38
3.2.2 Moisture Content Determination ---------- 38
3.2.3 Total Soluble Solids (TSS) Measurement ---------- 39
3.2.4 Dielectric Properties Measurement and Sample Preparation ---------- 39
3.3 Dehydrated Product Quality Analysis ---------- 42
3.3.1 Color Measurements ---------- 42
3.3.2 Rehydration Test ---------- 43
3.3.3 Micro-structural Analysis ---------- 43
3.4 Modeling of Drying Process ---------- 45

3.4.1 Moisture Ratio Determination -- 45
3.5 Statistical Analysis -- 47
3.5.1 Chemical Pretreatment -- 47
3.5.2 Osmotic Dehydration -- 47
3.5.3 Drying Experiments--- 48
Chapter IV – DEVELOPMENT OF A MICROWAVE DRYER SYSTEM ----------- 49
4.1. Configuration of Microwave-Convection Oven -------------------------------- 49
4.2. Microwave and Convection System Instrumentation ------------------------- 50
4.3. Convection Air Temperature Controller Installation ------------------------- 51
4.3.1 Airflow Rate Measurement--- 55
4.4 Data Acquisition Module Integration --- 55
4.4.1. Temperature Data Acquisition -- 56
4.4.2. Data Acquisition Software-- 57
4.4.3. Online Weight-Loss Measurement-- 57
4.5. Standard Reference Material (Water) Testing--------------------------------- 60
4.6 Summary of Chapter IV -- 62
CHAPTER V – RESULTS AND DISCUSSION -- 64
5.1. Chemical Pre-treatment Experiments -- 64
5.1.1. Effect on Osmotic Dehydration --- 66
5.2. Osmotic Dehydration (OD) Experiments--- 68
5.2.1. Effect on Moisture Loss and Solid Gain ---------------------------------- 69
5.2.3. Effect on Dielectric Properties-- 73
5.3. Drying Characteristics --- 75
5.3.1. Drying Time--- 76
5.3.2. Effect of Drying Mode -- 79
5.3.3. Effect of Osmotic Dehydration on Drying---------------------------------- 81
5.4. Modeling of Drying Process --- 83
5.4.1. Evaluation of Thin-layer Drying Equation -------------------------------- 83
5.4.2. Data Analysis-- 83
5.4.3. Quality Analysis-- 89
5.5 Summary of Chapter V-- 93

CHAPTER VI - CONCLUSIONS ---------- 94
6.1 Conclusions ---------- 94
6.2. Recommendations for Future Work ---------- 96
References ---------- 97
APPENDIX ---------- 104
Appendix A1. Microwave Combination Drying at 60, 70 and 80^{o}C ---------- 105
Appendix A2. Microwave drying at 60, 70 and 80^{0}C ---------- 107
Appendix A3. Convection drying at 60, 70 and 80^{0}C ---------- 109
Appendix A4. Temperature trends during microwave drying at 60^{o}C. ---------- 115
Appendix B1. Microwave drying of fresh blueberries ---------- 116
Appendix C1. Dielectric properties of saskatoon berries ---------- 117
Appendix D1. Scanning Electron Microscope images of saskatoon berries - 121
Appendix E1. Digital Images of Experimental Setup ---------- 122

LIST OF TABLES

Table 2.1 Nutrient values of berries grown in Western Canada ----------------------7
Table 2.2 Physico-chemical characteristics of five saskatoon cultivars-------------7
Table 2.3 Saskatchewan statistics for Horticulture products (2001 Census of Agriculture) --8
Table 2.4 Canadian Statistics for Horticulture products (2001 Census of Agriculture) --9
Table 2.5 Number of acres of fruit crops planted in the Province of Saskatchewan in the year 2004 -- 10
Table 2.6 Major fruit processing and research centers in the Province of Saskatchewan -- 10
Table 3.2 Drying models fitted for the drying data------------------------------------- 46
Table 4.1 Measured output power of the microwave system ------------------------ 61
Table 5.1 Moisture content and Total soluble solids of osmotic dehydrated berries after chemical pre-treatment --- 65
Table 5.2 Solid gain and Moisture loss during osmotic dehydration from 6 to 36 h duration--- 69
Table 5.3 Drying time and drying rate for untreated saskatoon berries------------ 77
Table 5.4 Drying time and drying rate for osmotic dehydration of saskatoon berries with sucrose (60% and 24h)-- 81
Table 5.5 Co-efficient of determination and standard error values for different equations-- 84
Table 5.6 Rehydration ratio of Microwave dried berries with and without osmotic dehydration --- 90
Table 5.7 Rehydration ratios of sucrose osmotic dehydrated berries at different drying conditions -- 91
Table 5.8 Hunterlab colorimeter parameters of untreated and sucrose pretreated berries under microwave, convection and combination drying conditions -- 92

LIST OF FIGURES

Figure 3.1 Stages of Saskatoon berry drying / dehydration process --------------- 34
Figure 3.2 Open-ended coaxial probe and adjustable platform---------------------- 41
Figure 3.3 Photograph of SEM system with computer -------------------------------- 44
Figure 3.4 Functional components and operating principle of Scanning Electron Microscope (SEM) --- 45
Figure 4.1 Front panels of the microwave drying system (left panel to set microwave power and run-time and right panel to set and monitor convection temperatures) -- 51
Figure 4.2 Teflon block fabricated to insert fibre optic temperature probes in to the microwave cavity -- 52
Figure 4.3 An assembly of fibre optic temperature sensors and signal conditioner for temperature measurement --- 52
Figure 4.4 Aerial view of the convection fan and the belt pulley arrangement --- 53
Figure 4.5 Flowchart of the convection heating system explaining the working operation of the convection heating circuit---------------------------------- 54
Figure 4.6 Temperature data acquisition flowchart explaining the step-by-step procedure adapted in temperature data acquisition ----------------------- 55
Figure 4.7 Temperature data acquisition main screen of LabView 6i program -- 56
Figure 4.8 Ohaus balance mounted on top of the microwave system to record online weight loss data --- 57
Figure 4.9 Weight-loss data acquisition flowchart indicating the step-by-step procedure adapted in temperature data acquisition ----------------------- 58
Figure 4.10 Sample holder connected to a weighing scale by nylon string ------- 59
Figure 4.11 Weight-loss data acquisition snap-shot of LabView program--------- 59
Figure 4.12 Sample holder with saskatoon berry dried samples with temperature sensors --- 60
Figure 5.1 Saskatoon berries brix levels (TSS) after Chemical Pre-treatment and 6 h Osmotic Dehydration with high fructose corn syrup ------------------ 64

Figure 5.2 Frozen berry cut section of the berry skin under SEM ------------------- 67
Figure 5.3 SEM of saskatoon berry osmotically dehydrated with 50% high fructose corn syrup (HFCS) solution for 24 h without chemical pre-treatment -- 67
Figure 5.4 SEM of saskatoon berry osmotically dehydrated with 50% sucrose solution for 24 h without chemical pre-treatment --------------------------- 68
Figure 5.5 Moisture loss during the 36 h osmotic dehydration in sucrose solution at 40, 50 and 60% concentrations -- 70
Figure 5.6 Moisture loss during 36 h osmotic dehydration in high fructose corn syrup (HFCS) solution at 40, 50 and 60% concentrations --------------- 70
Figure 5.7 Solute gain during 36 h osmotic dehydration in sucrose solution at 40, 50 and 60% concentrations-- 71
Figure 5.8 Solute gain during 36 h osmotic dehydration in high fructose corn syrup solution at 40, 50 and 60% concentrations -------------------------- 72
Figure 5.9 Osmotic dehydration effects on dielectric properties after 12 and 24 h durations at 50% high fructose corn syrup Concentration --------------- 73
Figure 5.10 Osmotic dehydration effects on dielectric properties at 40, 50 and 60% high fructose corn syrup concentrations and respective frequencies (915 and 2450 MHz) -- 74
Figure 5.11 Drying temperature trends at combination P1, P2 and P3 levels (60, 70 and 80^{o}C respectively) and its effect on drying time ------------------ 78
Figure 5.12 Drying temperature trends at microwave P1, P2 and P3 power levels (60, 70 and 80^{o}C respectively) and its effect on drying time ------------ 79
Figure 5.13 Drying of untreated berries at 70^{o}C under Microwave, Convection and Combination drying conditions --- 80
Figure 5.14 Microwave drying of osmotically treated and untreated berries at 70^{o}C -- 82
Figure 5.15 Midilli equation drying curve fit for sucrose osmotic dehydration combination drying at 60^{o}C -- 85
Figure 5. 16 Modified drying equation drying curve fit for sucrose combination drying at 80^{o}C -- 86

Figure 5.17 Midilli equation drying curve fit for sucrose osmotic dehydration microwave drying at 70^{o}C-- 87
Figure 5.18 Midilli equation drying curve fit for sucrose osmotic dehydration convection drying at 70^{o}C-- 88
Figure 5.19 Sharma's equation drying model curve fit for combination drying method at 60^{o}C -- 89
Figure A1 Microwave combination drying of untreated saskatoon berries at 60, 70 and 80^{0}C temperatures and corresponding weight loss plotted against time (min) --- 105
Figure A2 Microwave combination drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 60, 70 and 80^{0}C temperatures and corresponding weight loss plotted against time (min)------------------- 106
Figure A3 Microwave drying (weight loss, g) of untreated saskatoon berries at 60, 70 and 80^{0}C temperatures and corresponding moisture loss plotted against time (min) --- 107
Figure A4 Microwave drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 60, 70 and 80^{0}C temperatures -------------------- 108
Figure A5 Convection drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 60^{0}C temperature ----------------------------------- 109
Figure A6 Convection drying (weight loss, g) of high fructose corn syrup osmotic dehydrated saskatoon berries at 60^{0}C temperature--------------------- 110
Figure A7 Convection drying (weight loss, g) of untreated saskatoon berries at 60^{0}C temperature -- 111
Figure A8 Convection drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 70^{0}C temperature ----------------------------------- 112
Figure A9 Convection drying (weight loss, g) of untreated saskatoon berries at 70^{0}C temperature -- 113
Figure A10 Convection drying (weight loss, g) of untreated saskatoon berries at 80^{0}C temperature -- 114

Figure A11 Microwave drying product temperatures of high fructose corn syrup treated saskatoon berries at 60^{0}C product temperature and corresponding air temperature (^{o}C) plotted against time (min) ------- 115
Figure B1 Blueberries disintegrated structure after low power microwave drying -- 116
Figure C1 Dielectric properties of frozen saskatoon berry syrup ------------------ 117
Figure C2 Dielectric loss factor variation of saskatoon berry syrup after osmotic dehydration with 40, 50 and 60% sucrose sugars solutions----------- 117
Figure C.3 Effect of high fructose corn syrup Concentration on Osmotic Dehydration--- 118
Figure C4 Dielectric loss factor (ε") variation with frequency of Fresh saskatoon berries-- 118
Figure C5 Dielectric properties of fresh whole, cut and syrup of berries--------- 119
Figure C6 Dielectric constant (ε’) variation with frequency of frozen saskatoon berries (whole and crushed)--- 119
Figure C7 Dielectric constant and Loss factor variation with frequency of water -- 120
Figure D1 Scanning electron microscope image of osmotically dehydrated berries with 50% sucrose solution --- 121
Figure E1 Frozen saskatoon berries-- 122
Figure E2 Thawed saskatoon berries placed in polycarbonate sample holder. 122
Figure E3 Panel to switch between preset and modified settings ----------------- 123
Figure E4 Front panel with temperature controller and setup to monitor convection and microwave run-time-- 123
Figure E5 Inverter technology built in the Panasonic microwave-convection system --- 124

LIST OF SYMBOLS AND GLOSSARY

MC	Moisture Content (%)
RH	Relative Humidity (%)
m/s	Airflow Rate Unit
brix	Total Soluble Solids Unit
MR	Moisture Ratio
k	Drying Constant (h^{-1})
W	Units of Power (Watts)
V	Voltage Unit (Volts)
P1, P2 and P3	Microwave Power Levels (In-built)
MC/min	Drying Rate Unit
Saskatoons	saskatoon berries
OD	Osmotic Dehydration
COR	Coefficient of Rehydration
SEM	Scanning Electron Microscope
MW	Microwave
RF	Radio Frequency
DAQ	Data Acquisition
HP	Hewlett-Packard
I/O	Input / output
HFCS	High Fructose Corn Syrup
ε'	Dielectric Constant
ε''	Dielectric Loss Factor
L	Lightness Indicator
a and b	Chromacity Coordinates
ΔE_{ab}	Total Color Difference
TSS	Total Soluble Solids (brix)
MHz	Unit of Frequency (Mega Hertz)

δ	Loss angle of dielectric
FSA	Food Standard Agency
EU	European Union
SSR	Solid State Relay

GLOSSARY OF TERMS

Equilibrium MC (EMC)	Moisture content of the material after it has been exposed to a particular environment for an infinitely long period of time.
Relative Humidity (RH)	Defined as ratio of vapor pressure of water in the air to the vapor pressure of water in saturated air at the same temperature and atmospheric pressure.
Osmotic - Dehydration (OD)	Two-way counter flow of fluids from food material into an osmotic solution through a semi-permeable membrane.
U-Pick	Harvesting operation for fruits where consumer picks fruits of desired quality and quantity on the farm.

CHAPTER I - INTRODUCTION

1.1 Introduction

The technique of dehydration is probably the oldest method of food preservation practiced by humankind. The removal of moisture prevents the growth and reproduction of microorganisms causing decay and minimizes many of the moisture-mediated deteriorative reactions. It brings about substantial reduction in weight and volume, minimizing packing, storage and transportation costs and enables storability of the product under ambient temperatures. These features are especially important for both developed and developing countries in military feeding and new product formulations.

Saskatoon berries (*Amelanchier alnifolia*), also known as saskatoons are grown primarily in the Prairie Provinces of Canada and the plains of the Unites States. Up to nine varieties of saskatoons are reported according to their habitat, flowering and ripening time, growth form and size, color, seediness and flavor for production (Turner, 1997). Certain varieties were more likely to be dried fresh like raisins for winter use, while others were cooked to the consistency of jam before being dried. The berries are an excellent source of vitamin C, manganese, magnesium, iron and a good source of calcium, potassium, copper and carotene. Because the edible seeds are consumed, the berries are also higher in protein, fat and fibre than most other fruits (Turner et al., 1990).

The length of saskatoon berry harvest ranges from 1 to 4 weeks. Many producers are not able to harvest and sell their entire crop during the short harvest season. Freezing on the farm has increased market flexibility for consumers, producers and processors by extending the length of time saskatoons are available. Frozen saskatoon berries are marketed for direct consumption and for processed product manufactures.

A sharp rise in energy costs has promoted a dramatic upsurge in interest in drying worldwide over the last decade. Advances in techniques and development of novel drying methods have made available a wide range of dehydrated products, especially instantly reconstitutable ingredients, from fruits and vegetables with properties that could not have been foreseen some years ago. Longer shelf-life, product diversity and substantial volume reduction are the reasons for popularity of dried berries, and this could be expanded further with improvements in product quality and process applications. These improvements could increase the current degree of acceptance of dehydrated berries (saskatoons, blueberries etc.) in the market. Microwave and microwave-combination drying could be a possible alternative to freezing of fresh berries. Freezing and storage of frozen berries is a cost and energy-intensive process involving cold storage costs for the whole bulk of material.

A very scant data currently exists on processing (drying, processing, packaging etc.) of fresh saskatoons to extend the shelf life. Even though drying of horticultural crops (fruits, vegetables and spices) has been reported, there is not much literature reported on drying / dehydration of saskatoon berries. Therefore, the overall objective of this study was to develop an integrated drying system suitable for berries (saskatoons, raspberries etc.) and in particular, to study the drying behavior of saskatoons and to compare the drying characteristics under microwave, convection and microwave-convection drying methods with respect to drying, shrinkage and rehydration characteristics obtained by these drying schemes.

1.2 Objectives

The specific objectives of this research were:

1. To modify, instrument and eventually develop the microwave-convection combination drying system for real-time weight-loss and temperature monitoring along with data acquisition.
2. To evaluate osmotic dehydration as a pre-treatment for drying and study its effect on dielectric properties, drying rate, and final berry quality.
3. Drying studies under microwave and microwave-convection combination and convective (thin-layer) conditions using the newly developed dryer and study the quality and sensory evaluation (rehydration, color, etc.) characteristics.

CHAPTER II – LITERATURE REVIEW

The Canadian production and processing situation for berries (strawberry, cranberries, blueberry, saskatoon berry, etc.) has become commercial in last two decades with increasing production and processing facilities. The following review will present the post harvest technology aspects for saskatoon berries, drying methods and effect of drying on quality factors of fruits.

2.1. Saskatoon Berries

Saskatoon berry (*Amelanchier alnifolia*) is the main species from which fruiting cultivars are derived. Other commonly used species include: *A. arborea* (Downy serviceberry), *A. asiatica* (Asian serviceberry), *A. canadensis* (shadblow seviceberry) and *A. laevis* (Allegheny serviceberry). Saskatoon berries are very versatile berries from the rose family (Rosaceae). They have long been treasured as a wild fruit and now with the growth in U-Pick saskatoon berry (saskatoons) orchards, the very best berries are available on the consumer market. The North American species of Amelanchier are variously called by the common names of saskatoon berry, serviceberry, juneberry, and shadberry.

Over the past two decades, however, there has been increasing interest in utilizing the cultivated production of this tasty berry as a unique Western Canadian fruit crop. Today, there are 100 to 200 hectares of cultivated saskatoons in production on the Canadian Prairies. Another 200 to 400 hectares have been planted, but are still too young to produce significant quantities. Consumers are attracted to the unique, subtle flavor of the “wild” fruit product made from saskatoon berries, and market survey indicates the potential for acceptance of saskatoon berry products is Worldwide. The berry orchards are found all over western North America. Nearly 250 producers now boast orchards covering nearly 1,000 acres, harvesting thousands of pounds of the native fruit and rapidly establishing a sophisticated new commercial segment of diversified Saskatchewan agriculture. Two years ago, production for the berry business revealed an output of two million pounds. There is a growing percentage of agricultural revenues as the fruit industry now includes ten processing plants and 300 full and part-time employees. A total of 240 Saskatchewan farm operations reported growing saskatoon berries on 916 acres. This was 31% of the Canadian total production area. Saskatchewan ranked second for saskatoon berry area after Alberta with 1,525 acres. Of these provinces, Saskatchewan is the largest processor of the berry (Mazza, 1982).

Processors use saskatoons to produce products such as syrups, jams, jellies, fillings, sauces, chocolates, muffins, liquors and wines. Processors require berries that have been cleaned, graded and frozen. The capacity to freeze berries, store-frozen berries and ship frozen berries throughout the year is essential in selling to this market. Fresh saskatoons have a short shelf life, even when refrigerated, but freeze very well and can maintain their quality for up to two years. Slow freezing produces microscopic cracks in berries through which the pigment-laden juice escapes (Sapers et al., 1985). Most of the freshly harvested berries are flash frozen within two hours, which has allowed sales to be extended year-round. Prior to packaging and/or processing all leaves and twigs are totally removed from the berries. Handling techniques of fresh berries are presently being standardized and grading / sorting criteria being regularized.

Presently, approximately 10-12% of saskatoon berries are sold fresh, but significant portions are frozen or canned. Lower quality fruit is used in jams and purees, where appearance is critical. Purees can be added to yogurt, ice cream and fruit smoothies. It is also anticipated that saskatoon berries will be used to enhance color and flavor of a variety of products, from specialty cheeses to nutritious snacks. Its dark color with its high nutritional content and associated to anthocyanin content will make it an attractive fruit to consumers. Combination of osmotic and air drying technology in blueberries has produced shelf-stable berries that maintains a pleasant chewy texture (Mazza et al., 1993). Little data currently exists on processing (drying, processing, packaging etc.) of fresh saskatoons to extend the shelf life and stability for packaging and distribution.

Researchers explain that a shortage of fresh saskatoon markets, however, is the biggest limiting factor for further growth in the industry. While the demand for the berries in their processed form may be great, there is significant demand for the fresh form. This is not surprising considering both taste and nutritional value are at their highest immediately following harvest. To date, saskatoons are not sold in large supermarkets as fresh fruit because flavor, structural integrity and quality of the fruit degrade rapidly within days of being picked.

Saskatoons are a rich source of vitamin C and are also known for their antioxidant qualities. Crude extracts of *Amelanchier utahensis* are being studied for use as cancer therapy drugs. Dried saskatoons can also be used in nutraceutical industry and extraction (Mazza, 1986).

2.1.1. Fruit Composition

The nutritional value of saskatoon berries on a dry weight basis is listed in Table 2.1. Saskatoon berries contain higher levels of protein, fat, and fiber than most other fruit. Panther and Wolfe (1972) reported negligible ascorbic acid content and that an ascorbic acid oxidizing enzyme system was present in the berries. Total solids content ranges from 20 to 29.4% fresh weight with 15.9 to 23.4% sucrose and 8 to 12% reducing sugars (Mazza, 1979; Mazza, 1982). Wolfe and Wood (1971) found that the sugar content increases slowly as the fruit matures and then accelerates markedly before ripening. Their results also indicated that fructose content decreased rather markedly (25%) after the fruit ripened while the glucose content remained unchanged. Berry pH values range from 4.2 to 4.4 and titratable acidity values (% malic acid) from 0.36 to 0.49% (Mazza, 1979; Green and Mazza, 1986).

Table 2.1 Nutrient values of berries grown in Western Canada

Per 100g	Saskatoons	Blueberries	Strawberries	Raspberries
Energy (Ca)	84.84	51	37	49
Protein (g)	1.33	0.42	0.7	0.91
Carbohydrate (g)	18.49	12.17	8.4	11.57
Total Lipid (g)	0.49	0.64	0.5	0.55
Total Fiber (g)	5.93	2.7	1.3	4.9
Vitamin C (mg)	3.55	2.5	59	25
Iron (mg)	0.96	0.18	1	0.75
Potassium (mg)	162.12	54	21	152
Vitamin A (IU)	35.68	100	27	130

Source: Saskatoon berries, SFGA, Conducted by POS Pilot Plant, assistance of Native Fruit Development Program (February 2003); Other fruit--USDA National Nutrient Database for Standard Reference, Report 15 (August 2002)

Table 2.2 Physico-chemical characteristics of five saskatoon cultivars

Cultivar	10 Berry wt (g)	pH	Titrable acidity (% malic acid)	Total Solids (% dry wt)	Soluble Solids (% sucrose)	SS/Ac	Anthocyanins mg/100g
Honeywood	12.7	3.8	0.54	25.6	18.7	34.7	114
Northline	8	3.9	0.45	25.1	16.1	35.5	111
Porter	7.8	3.8	0.56	22.7	16.3	29.5	108
Regent	6.8	4.4	0.29	20.8	14.8	52.8	72
Smoky	10.1	4.5	0.25	27	16.3	66.2	68

Source: Saskatoon berries, SFGA, Conducted by POS Pilot Plant, assistance of Native Fruit Development Program (February 2003); Other fruit--USDA National Nutrient Database for Standard Reference, Report 15 (August 2002)

The predominant acid in saskatoon berries is malic (Wolfe and Wood, 1972) and the predominant aroma component is benzaldehyde (Mazza and Hodgins, 1985). There are at least four anthocyanins in ripe saskatoon berries; cyanidin 3-galactoside accounts for about 61% and 3-glucoside for 21% of total anthocyanins (Mazza, 1986). A detailed list of all the physico-chemical characteristics of five saskatoon varieties is listed in Table 2.2.

2.1.2. Production and Post-harvest Technology

Commercial saskatoon berry production is practiced in horticultural orchards and marketed in consumer and processor markets including farmer's market. The saskatoon berry is well known in the Prairies; however it is relatively unknown in other areas. As a result, the present market for saskatoons tends to be in the Prairies. Production statistics for the province of Saskatchewan and Canada is listed in Table 2.3 and Table 2.4. In Saskatchewan, the number of acres growing berries and grapes in 2001 was 542 that are more than twice when compared to 1991 statistics. The long-term market opportunity for saskatoons lies in reaching consumers in other locations. The majority of saskatoons growers operate as U-pick or market garden enterprises. However, the greatest portion of the berries produced in Alberta is sold to processors. New entrants to the industry are likely to start out as U-pick operators. As they become established with larger acres, a larger portion of the crop is likely to be sold to processors rather than as fresh berries.

Table 2.3 Saskatchewan statistics for Horticulture products (2001 Census of Agriculture)

(Saskatchewan)	1981	1986	1991	1996	2001
Total number of farms	67,318	63,431	60,840	56,995	50,598
Total berries and grapes (Ha)	8	120	225	443	542
Total vegetables (Ha)	595	491	422	477	397

1. Conversion factor: 1 hectare equals 2.471 acres.
2. Conversion factor: 1 square meter equals 10.76391 square feet.
Source: Statistics Canada, Census of Agriculture.

Table 2.4 Canadian Statistics for Horticulture products (2001 Census of Agriculture)

(Canada)	1981	1986	1991	1996	2001
Total number of farms	318,361	293,089	280,043	276,548	246,923
Total berries and grapes (Ha)	31,458	40,470	45,759	57,523	69,165
Total vegetables (Ha)	117,216	116,573	122,594	127,697	133,851

1. Conversion factor: 1 hectare equals 2.471 acres.
2. Conversion factor: 1 square meter equals 10.76391 square feet.
Source: Statistics Canada, Census of Agriculture

2.1.2.1. Saskatchewan Fruit Sector

Fruit handling and processing is an emerging industry in Saskatchewan. The industry has grown out of a maturing U-Pick based industry, which began in 1980. As recently as fifteen years ago, fruit processing facilities were virtually non-existent in the province. It is now a well diversified industry supplying fresh, frozen and processed fruit products to the wholesale and retail trades, and expanding export markets of frozen and processed fruit products in Europe.

In keeping with recent developments, the fruit production industry is ensuring that they receive proper on-farm food safety training, and thirteen of the major fruit processors in the province now have federally inspected plants. There are approximately 30 fruit processors in the province in total including two wineries established through the Cottage Winery Policy of the Saskatchewan Liquor and Gaming Authority and based predominantly on Saskatchewan grown fruits.

In 2004, there were approximately 550 fruit growers in the province and an estimated 1,800 acres planted to fruit crops (Table 2.5).

Table 2.5 Number of acres of fruit crops planted in the Province of Saskatchewan in the year 2004

No.	Fruits Planted	Acres
1	Saskatoon berry	1200 - 1300
2	Strawberry	250
3	Dwarf Sour Cherry	125 -150
4	Apple	100
5	Raspberry	80 - 100
6	Chokecherry	80 -100
7	Blue Honeysuckle	20
8	Black Currant	15

Source: Canada's Fruit Industry, Government of Canada, http://ats.agr.ca

Table 2.6 Major fruit processing and research centers in the Province of Saskatchewan

No.	Food Processing / Research Centre	City
1	Berryview Farms	Lloydminster
2	C and V Orchards	Weyburn
3	Dawn Food Products (Canada) Ltd.	Saskatoon
4	Gramma Beps	Swift Current
5	Harvest Pie	Pangam
6	Heavenly Hills Orchard	Blaine Lake
7	Last Mountain Berry Farms	Southey
8	Nature Berry	Air Ronge
9	Parenteau's Saskatoon Berry	Langham
10	Prairie Berries Inc.	Keeler
11	Riverbend Plantation	Saskatoon
12	Saskatchewan Food Development Centre	Saskatoon
13	Saskatchewan Food Centre	Saskatoon
14	University of Saskatchewan (Ag Eng. College)	Saskatoon

Source: Canada's Fruit Industry, Government of Canada, http://ats.agr.ca

Producers and processors originally focused on four major crops: saskatoon berry, strawberry, chokecherry and sea buckthorn. The industry is now rapidly expanding production to include a number of new crops. With recent developments in the domestic fruit program at the Department of Plant Sciences, University of Saskatchewan, the industry is now also focusing on dwarf sour cherries, blue honeysuckle, dwarf apples and black currant. There are 10 major processors marketing frozen and processed fruit and fruit products in Saskatchewan (Table 2.6) and approximately 70 people employed in the fruit processing industry.

2.1.2.2. International Market Access for saskatoon berries

A retail chain in the United Kingdom marketed Canadian saskatoon berries this past winter. Shortly after introducing saskatoons to the market, the importer and the retailer were advised by the U.K. Food Standards Agency (FSA) that saskatoons could not be sold in the United Kingdom until they had been approved as being safe for consumption under the European Union (EU) Novel Foods Regulations (Regulation 258/97).

On December 10, 2004, a committee of EU member states declared that the berries are not novel. This means that the EU market is currently open to Canadian saskatoon berries and Canadian exports of the berry can resume. Canada will continue to monitor the situation in the coming months to ensure that exports of saskatoon berries are able to enter the European Union without mishap.

2.1.3. Freezing vs. Drying

The frozen fruit and vegetable industry uses much energy in order to freeze the large quantity of water present in fresh product. As pointed out by Huxsoll (1982), a reduction in moisture content of the material reduces refrigeration load during freezing. Other advantages of partially concentrating by osmotic dehydration (OD) or sugar infusion fruits and vegetables prior to freezing includes savings in packaging and distribution costs and achieving higher product quality because of the marked reduction of structural collapse and dripping while thawing. Further drying of the product can be performed for preservation or utilization for product preparations.

The advantages of drying of fruits and vegetables as against freezing are:

- Large energy consumption for freezing and also to maintain the fruit in frozen condition till it is either consumed or processed,
- As the bulk volume is not reduced due to freezing more storage space is required that again adds to the storage costs,
- Drying reduces the moisture content of the produce that has an impact of lowering the microbiological activity in the fruit, and
- Drying without freezing the product itself will avoid the energy consumption for freezing and in new product development.

The saskatoon berry is a very new commercial fruit, yet several food processors are already using wild and cultivated berries in their food products. There seems to be considerable potential for expansion of production and processing of saskatoon berry as many processors and distributors have reported they would use large quantities of this unique fruit if they had an assured supply at a reasonable price.

2.2 Fruit Pretreatment

Fruit pretreatments including chemical pretreatment, freezing, thawing and osmotic dehydration can influence the dehydration or drying rates as well as maintain an overall quality of the final product.

2.2.1. Chemical Pretreatment

Waxy layer in the skin makes it difficult to dry the product. Dehydration of small fruits; such as grapes, blueberries, cranberries, cherries and gooseberries, is restricted by the outer surface (cuticle) which plays a major role in the control of transpiration and in protecting the fruit against weather in clemencies or attacks from insects and parasites (Somogyi and Luh, 1986; Somogyi et al., 1996).

According to Kostaropoulus and Saravacos (1995) and Grabowski et al. (1994), the drying time of surface pretreated grapes (immersed in ethyl oleate, etc) was reduced by about half. Venkatachalapathy and Raghavan (1997) found a positive effect using a combination of ethyl oleate (2%) and NaOH (0.5%) for microwave drying of grapes. However, the convective drying rate of the strawberries was improved by only about 10% as a result of this pretreatment. Salunkhe et al. (1991) had reported that alkaline dipping facilitates drying by forming fine cracks on the fruit surface that was determined by Ponting and McBean (1970) that, pre-treating with ethyl esters of fatty acids would be the effective treatment for fruits with waxy surface layer. Tulasidas et al. (1993) reported that pre-treating with ethyl oleate could improve the drying rate. Venkatachalapathy (1997) used an alkaline solution of 2% ethyl oleate and 0.5% sodium hydroxide (NaOH) as a pre-treatment for strawberries and blueberries. The above authors have also dried osmotically pretreated cranberries.

2.2.2 Osmotic Dehydration

The use of osmosis allows both ways of decreasing water activity in food to be applied simultaneously. The permeability of plant tissue is low to sugars and high molecular weight compounds; hence the material is impregnated with the osmo-active substance in the surface layers only. Water, on the other hand, is removed by osmosis and cell sap is concentrated without a phase transition of the solvent. This makes the process favorable from the energetic point of view. The flux of water is much larger than the counter current flux of osmoactive substance. For this reason the process is called osmotic dehydration or osmotic dewatering.

The food produced by this method has many advantageous features:

- It is ready to eat and rehydration is not needed,
- The amount of osmoactive substance penetrating the tissue can be adjusted to individual requirements,
- The chemical composition of the food can be regulated according to needs, and
- Mass of raw material can be reduced by 20% to half.

The osmotic dehydration does not reduce water activity sufficiently to hinder the proliferation of microorganisms. The process extends, to some degree, the shelf life of the material, but it does not preserve it. Hence, the application of other preservation methods, such as freezing, pasteurization, or drying is necessary. However, processing of osmotically dehydrated semi products is much less expensive and preserves most of the characteristics acquired during the osmosis.

2.2.2.1 Osmo-active Substances

Osmo-active substance used in food must comply with special requirements. They have to be edible with accepted taste and flavor, nontoxic, inert to food components, if possible, and highly osmotically active. Sucrose, lactose, glucose, fructose, maltodextrins and starch or corn syrups are commonly used in osmotic dehydration of fruits and vegetables. Glucose and fructose give a similar dehydration effect (Sarosi and Polak, 1976). In other publications it is reported that fructose increases the dry matter content by 50% as compared with sucrose. Starch syrup makes it possible to have similar final water content in dehydrated material as that obtained with sucrose but at a much lower influx of osmoactive substance into tissue (Lenart and Lewicki, 1990). The dextrose equivalent of the syrup affected strongly the ratio between water loss and solids gain.

2.2.2.2 Product Characteristics

Osmotic dehydration is a complex process of countercurrent mass transfer between the plant tissue and hypertonic solution. This leads to dehydration of the material and changes in its chemical composition as well. Hence, it must be expected that the properties of the material dehydrated by osmosis will differ substantially from those dried by convection.

The flux of osmoactive substance penetrating the osmosed tissue changes its chemical composition. It has been shown that the content of sucrose increases in cell sap during osmotic dehydration (Hawkes and Flink, 1978; Dixon et al., 1976), and the sucrose flux is increased by the presence of sodium chloride (Islam and Flink, 1982). On the other hand, use of starch syrup gives only a small influx of sugars to the material (Contreras and Smyrl, 1981).

As it has been stated previously osmotic dehydration cannot be treated as a food preservation process. It is a pretreatment that removes a certain amount of water from the material; to achieve shelf stability a further processing of the product is needed. Hence, the interaction of osmotic dehydration with further processing is important for quality assurance. Use of osmotic dehydration practically eliminates the need to use preservatives such as sulfur dioxide in fruits (Ponting et al., 1966).

In osmotic dehydration, pieces of fruit or vegetable are immersed in a aqueous solution. Sucrose or mixtures of sugars are normally used for fruits. Because the cell membranes only allow very limited transfer of sugars into the tissue, equalizing the concentrations of dissolved substances inside and outside the fruit takes place by movement of the water from the inside to the outside. The material may also lose a portion of its own solutes (vitamins, volatiles, minerals, etc.).

Osmotic dehydration can be used as an effective method to remove water from fruit and vegetable tissues while simultaneously introducing solutes in the product. For dried vegetables, which will be applied in savourily instant foods, NaCl is the preferred osmotic solute. With the osmotic dehydration technique shelf stability cannot be obtained. This requires a further decrease of the water activity. Further moisture removal by evaporation at intermediate moisture content after osmotic dehydration is necessary to reach final moisture content for achievement of shelf stability.

2.3 Fruit Preservation Techniques

Fruits are high moisture foods with higher respiration rate and prone to microbiological deterioration. Harvested fruits are to be processed to extend its shelf life. In this section, we discuss about the different fruit preservation methods and in particular the saskatoon berries.

2.3.1 Dehydration / Drying

Dehydration is a means of preserving the safety and quality of foods at the forefront of technological advancements in the food industry. It has greatly extended the consumer acceptable shelf life of appropriate commodities from a few days and weeks to months and years. The lower storage and transportation costs associated with the reduction of weight and volume due to water removal have provided additional economic incentives for widespread use of dehydration processes. The expanding variety of commercial dehydrated foods available today has stimulated unprecedented competition to maximize their quality attributes, to improve the mechanization, automation, packaging, and distribution techniques and to conserve energy.

2.3.2 Introduction to Agri-Food Material Drying

It is well known that processes may affect (partially or totally) the quality of a product. Indeed, various changes in physical, chemical and / or biological characteristics of foodstuffs may occur during processing, storage and distribution. These changes alter the physical aspects such as color and structure. They can also develop undesirable biochemical reactions such as deterioration of aroma compounds or degradation of nutritional substance (Achanta and Okos, 1996). All the fore-mentioned physical and biochemical changes certainly cause reduction in product quality and in process efficiency as well (Chuy and Labuza, 1994). Particularly when dealing with high-value foods, the choice of the right method of preservation can therefore, be the key for a successful operation.

The term drying refers generally to the removal of moisture from a substance. It is the most common and most energy-consuming food preservation process. With literally hundreds of variants actually used in drying of particulate solids, pastes, continuous sheets, slurries or solutions, it provides the most diversity among food engineering units operations (Ratti and Mujumdar, 1995). Air-drying, in particular is an ancient process used to preserve foods in which the solid to be dried is exposed to a continuously flowing hot stream of air where moisture evaporates. The phenomenon underlying this process is a complex problem involving simultaneous mass and energy transport in a hygroscopic, shrinking system. Air-drying offers dehydrated products that can have an extended life of a year but, unfortunately, the quality of a conventionally dried product is usually drastically reduced from that of the original foodstuff.

2.3.2.1 Equilibrium Moisture Content

The moisture content remaining in a dry material, when the drying rate drops to zero at specified conditions of the drying medium is called the equilibrium moisture content. It is in equilibrium with the vapor contained in the drying gas, and its magnitude is a function of the structure and type of the subject food and of the prevailing drying conditions. The equilibrium moisture values predicted by the static and dynamic moisture sorption do not always agree over the whole range of relative humidity of the drying air.

2.3.2.2 Energy Requirement

The general case of drying of food materials involves energy inputs to meet the following energy requirements:

- Removal of free water through sublimation or evaporation,
- Removal of water associated with the food matrix,
- Superheating of water vapor sublimed or evaporated as it passes through the food, and
- Internal energy changes, i.e., the supply of sensible heat to the foodstuff as it changes temperature.

The energy of superheating the vapor and changing the internal energy of the food can usually be neglected inasmuch as the supply of sensible heat is usually minimal, on the order of the magnitude of the heat of vaporization / sublimation. The energy required to remove water from the food matrix will thus be given by the sum of the first two items.

2.4 Electrical Properties of Foods

Measurement of dielectric properties of agricultural material is essential for understanding their electrical behavior (Nelson, 1973) level of mechanical damage (Al-Mahasneh et al., 2000) and also for the development of indirect non-destructive methods for determining their physical characteristics, including moisture content and bulk density. Venkatesh et al. (1998) found that corn samples chopped to different degrees showed a difference in dielectric response at similar bulk densities and moisture contents which indicated that some of the response was due to the chopping or size reduction. They also reported that the results were not conclusive, since slight differences in moisture content and composition as well as measurement errors might have existed and could have had some effect on the results. They explained that the cross-sectional moisture and material gradients in the single grain kernels had an effect on the dielectric response of those kernels. The dielectric properties of a food depend upon its composition. It is beneficial to conduct dielectric properties measurements for each product that is to undergo a dielectric heating process.

The high frequency range is very large and it can be subdivided into kHz high frequency (10 kHz to 1MHz) and MHz frequency (1 to 300MHz). It is the latter range, which is used here when speaking about high frequency heating. The microwave frequency, which is located above high frequencies, is designated as between 300 MHz and 300 GHz, and microwave heating is defined as the heating of a substance by electromagnetic energy operating in frequency range mentioned above (Risman, 1991). Dielectric properties are of primary importance to evaluate the suitability and efficiency of microwave heating of the osmotically pretreated products. Furthermore, dielectric properties give insight in expected heat dissipation, temperature-time profiles and heating homogeneity.

2.4.1 General Principles – Dielectric Properties

The dielectric properties of usual interest are the dielectric constant (ε'), dielectric loss factor (ε") and penetration depth (D_p). ε' and ε" are the real and imaginary parts, respectively, of relative complex permittivity (ε^r).

The dielectric properties are often defined by the complex permittivity equation (Nelson, 1973):

$$\boldsymbol{\varepsilon^r = \varepsilon' - j\varepsilon''} \quad \textbf{(2.1)}$$

Where,

$\boldsymbol{\varepsilon^r}$= Complex permittivity,

$\boldsymbol{\varepsilon'}$= Dielectric Constant (Real part), and

$\boldsymbol{\varepsilon''}$= Dielectric Loss Factor (Imaginary part).

Values that can be presented are those of the dielectric constant, ε', and the dielectric loss factor, ε'', respectively, the real and imaginary parts of the complex relative permittivity, $\varepsilon = \varepsilon' - j\varepsilon''$ (Nelson, 1973). Values for the loss tangent, $\tan\delta = \varepsilon'' / \varepsilon'$ (where δ the loss angle of the dielectric) can be calculated from the ε' and ε'' values. The dielectric constant, loss factor, and loss tangent (sometimes called the dissipation factor) are dimensionless quantities.

Many molecules are dipolar in nature; that is, they possess an asymmetric charge center. Water is typical of such a molecule. Other molecules may become "induced dipoles" because of the stresses caused by the electric field. Dipoles are influenced by the rapidly changing polarity of the electric field. Although they are normally randomly oriented, the electric field attempts to pull them into alignment. However, as the field decays to zero, the dipoles return to their random orientation only to be pulled toward alignment again as the electric field builds up to its opposite polarity. This buildup and decay of the field, occurring at a frequency of many millions of times per second, causes the dipoles similarly to align and relax millions of times per second. This causes an energy conversion from electrical field energy to stored potential energy in the material and then to stored random kinetic or thermal energy in the material.

2.4.2 Influence of Moisture Content

The amount of free moisture in a substance greatly affects its dielectric constant since water has a high dielectric constant, approximately 78 at room temperature; that of base materials is of the order of 2 (Mudgett et al., 1974). Thus, with a larger percentage of water the dielectric constant generally increases, usually proportionally.

A few rules of thumbs are (Mujumdar, 1995):

- The higher the moisture content, usually the higher is the dielectric constant,
- The dielectric loss usually increases with increasing moisture content but levels off at values in the range of 20 to 30% and may decrease at still higher moisture, and
- The dielectric constant of moisture usually lies between that of its component.

Since drying is concerned with removal of water or a solvent, it is interesting to note that as these liquids are removed the dielectric loss decreases and hence, the material heats less well. In many cases this leads to self-limitation of the heating as the material becomes relatively transparent at low moisture content.
At low moisture contents, below the critical moisture content, we are dealing primarily with bound water; above it we encounter primarily free water. The dielectric loss of bound water is very low since it is not free to rotate under the influence of the electromagnetic field. This is seen in an analogous situation with ice, which has a dielectric loss factor of approximately 0.003 and that of water is approximately 12.

2.4.3 Influence of Density

The dielectric constant of air is 1.0 and that is for all practical purposes, transparent to electromagnetic waves at industrial frequencies. Therefore, its inclusion in materials reduces the dielectric constants, and as density decreases so do the dielectric properties and heating is reduced (Nelson, 2001). Density variation causes reduction of pore space and increase in dielectric constant and loss factor values.

2.4.4 Influence of Temperature

The temperature dependence of a dielectric constant is quite complex, and it may increase or decrease with temperature depending upon the material. In general, however, a material below its freezing point exhibits lowered dielectric constant and dielectric loss (Nelson, 2001). Above freezing the situation is not clear-cut, and since moisture and temperature are important to both drying and dielectric properties, it is important to understand the functional relationships in materials to be dried. Wood, for example, has a positive temperature coefficient at low moisture content; that is, its dielectric loss increases with temperature. This may lead to runaway heating, which in turn will cause the wood to burn internally if heating continues once the wood is dried.

2.4.5 Importance of Dielectric Properties

Dielectric properties are of primary importance to evaluate the suitability and efficiency of microwave (MW) heating of the osmotically pretreated products. Furthermore, dielectric properties give insight in expected heat dissipation, temperature-time profiles and heating homogeneity. The aim of dielectric properties measurement after osmotic dehydration and chemical pretreatments were to evaluate:

- Effects of osmotic dehydration and chemical pretreatments on dielectric properties of berries,
- Effect of chemical pretreatment on osmotic dehydration, and
- Measure and report dielectric properties of saskatoon berries before and after osmotic pretreatments.

2.4.6 Dielectric Measuring Systems

Many measurement techniques for measuring permittivity are available; their advantages and limitations determine the choice of the measuring system. Measurements of the dielectric properties are performed by numerous methods employing various sizes and shapes of materials (Westphal et al., 1972). At frequencies of interest for dielectric heating below 200 MHz, impedance bridges and resonant circuits have traditionally been used to determine the characteristics of capacitive sample holders with and without a dielectric sample from which the dielectric properties are calculated. At frequencies above 200 MHz and into the microwave region, transmission-line and resonant techniques have been useful.

2.4.6.1 Open-ended Coaxial Line Probe Technique

The coaxial probe is a convenient and broadband technique for lossy (low dielectric loss factor) liquids and solids (Venkatesh, 1998). It is non-destructive and little or no sample preparation is required for liquids or semi-solids. In the case of a solid material under test, the material face must be machined at least as flat as a probe face, as any air gap can be a significant source of error. It operates at frequencies between 45 MHz and 26.5 GHz. The technique assumes the material under test to be non-magnetic and uniform throughout. It should be noted that the accuracy in the coaxial probe measurements is dependent on both frequency and dielectric constant, with the best attainable accuracy being 5% in the real part of the permittivity and ±0.05 in loss tangent. Therefore this dielectric measurement system allows measurement of dielectric properties of materials with relatively high dielectric loss factor values, over the frequency range between 30 MHz and 45 GHz, including two microwave frequencies of 915 MHz and 2450 MHz that are allocated by the U.S. Federal Communications Commission (FCC) for Industrial, Scientific, Medical and Domestic (ISMD) heating applications.

2.4.6.2 Transmission Line Technique

This technique is cumbersome because the sample must be made into a slab or annular geometry (Raghavan et al., 2005). At 2450 MHz the sample size is somewhat large particularly for fats and oils. Commonly available waveguide test equipment for 2450 MHz is designated WR-284. For measurements at 915 MHz only the coaxial line technique is practical due to the large size of waveguide required. Liquids and viscous fluid type foods can be measured with this method by using a sample holder at the end of a vertical transmission line.

2.4.6.3 Waveguide and Coaxial Transmission Line Method

The dielectric properties could be determined by measuring the phase and amplitude of a reflected microwave signal from a sample of material placed against the end of a short-circuited transmission line such as a waveguide or a coaxial line. For a waveguide structure, rectangular samples that fit into the dimensions of the waveguide at the frequency being measured are required. For coaxial lines, an annular sample is needed (Venkatesh, 1996).

2.5 Drying Systems

Different drying systems applicable for drying agricultural material drying will be discussed in this section and importance will be given to microwave drying and combination drying methods.

2.5.1 Hot-air Drying

The most common drying method employed for food materials to date has been hot air drying (Mujumdar, 1995). But there are many disadvantages for this method. Among these are low energy efficiency and lengthy drying time during the falling rate period. This is mainly caused by rapid reduction of surface moisture and consequent shrinkage, which often results in reduced moisture transfer and, sometimes, reduced heat transfer (Feng and Tang, 1998). Due to the low thermal conductivity of food materials in this period, heat transfer to the inner sections of foods during conventional heating is limited (Feng and Tang, 1998). Several investigators of drying have reported that hot-air drying, hence prolonged exposure to elevated drying temperatures, resulted in substantial degradation in quality attributes, such as color, nutrients, flavor, texture, severe shrinkage, reduction in bulk density and rehydration capacity, damage to sensory characteristics and solutes migration from the interior of the food to the surface (Bouraout et al., 1994; Yongsawatdigul and Gunasekaran, 1996; Feng and Tang, 1998; Maskan, 2000).

2.5.2 Cabinet Dryers

Cabinet dryers are small-scale dryers used in the laboratory and pilot plants for the experimental drying of fruits and vegetables. They consist of an insulated chamber with trays located one above the other on which the material is loaded and a fan that forces air through heaters and then through the material by cross flow or through flow.

2.5.3 Tunnel Dryers

Tunnel dryers are basically a group of truck and tray dryers widely used due to their flexibility for the large scale commercial drying of various types of fruits and vegetables. In these dryers trays of wet material, stacked on trolleys, are introduced at one end of a tunnel (a long cabinet) and when dry are discharged from the other end. The drying characteristic of these dryers depends on the movement of airflow relative to the movement of trucks, which may move parallel to each other either concurrently or counter currently, each resulting in its own drying pattern and product properties.

2.5.4 Microwave Heating

Throughout history there has been one way to heat materials: apply heat to its surface. About thirty years ago, industrial engineers began developing microwave-heating techniques that avoid some limitations of conventional heating. With microwaves a form of radio waves (neither nuclear nor ionizing radiation) passes through the material. The molecules in the material then act like miniature magnets attempting to align themselves with the electrical field. Under the influence of this high frequency alternating electrical field, the particles oscillate about their axes creating intermolecular friction, which manifests itself as heat.

2.5.4.1 Advantages of Microwave Heating

In conventional heating the heat source causes the molecules to react from the surface toward the center so that successive layers of molecules heat in turn. The product surfaces may be in danger of over heating by the time heat penetrates the material. Microwaves, however, produce a volume heating effect. All molecules are set in action at the same time. It also evens temperature gradients and offers other important benefits. Heating and drying with microwave and dielectric energy is distinctly different from conventional means, whereas conventional methods depend upon the slow march of heat from the surface of the material to the interior as determined by differential in temperature from a hot outside to a cool inside, heating with dielectric and microwave energy is, in effect, bulk heating in which the electromagnetic field interacts with the material as a whole. The heating occurs nearly instantaneously and can be very fast, although it does not have to be. However, the speed of heating can be an advantage, and it is often possible to accomplish in seconds or minutes what could take minutes, hours and even days with conventional heating and processing methods.

A list of advantages of microwave and dielectric heating includes the following (Mujumdar, 1995):

- Process speed is increased,
- Uniform heating may occur throughout the material. Although not always true, often the bulk heating effect does produce uniform heating, avoiding the large temperature gradients that occur in conventional heating systems,
- Efficiency of energy conversions. In this type of heating, the energy couples directly to the material being heated. It is not expended in heating the air, walls of the oven, conveyor or other parts. This can lead to significant energy savings. Also, the energy source is not hot and plant-cooling savings may be realized,
- Better and more rapid process control. The instantaneous on-off nature of the heating and the ability to change the degree of heating by controlling the output power of the generator means fast, efficient and accurate control of heating,
- Floor space requirements are usually less. This is due to the more rapid heating,
- Selective heating may occur. The electromagnetic field generally couples into the solvent, not the substrate. Hence, it is the moisture that is heated and removed, whereas the carrier or substrate is heated primarily by conduction. This also avoids heating of the air, oven walls, conveyor or other parts,
- Product quality may be improved. Since high surface temperatures are not usually generated, overheating of the surface and case hardening, which

are common with conventional heating methods are eliminated. This often leads to less rejected product, and

- Desirable chemical and physical effects may result. Many chemicals and physical reactions are promoted by the heat generated by this method, leading to puffing, drying, melting, protein denaturation, starch gelatinization and the like.

Applying microwave energy to drying could eliminate some of the problems associated with conventional hot air drying methods. However, microwave drying has also been associated with physical damage to the products e.g. scorching, over heating or charring and uneven temperature distribution. Such physical damage is the result of local temperatures rising continuously even though the loss factor of material being dried decreases with the reduction in moisture content. Alternatively, combination of microwave with hot-air convection flow or vacuum can reduce the localized heating by creating a high temperature environment in the product surface surroundings and remove surface moisture driven by microwaves more efficiently.

2.5.5 Infrared Drying

Infrared energy has the ability to penetrate an object apart from conversion of electromagnetic energy into heat. The depth of penetration of infrared is a function of its wavelength. As a general statement, the shorter the wavelength, the greater is its penetration power. Infrared increases surface temperature; this in turn increases surface evaporation. For biological materials, however, infrared heater temperatures greater than 830^{o}C should be avoided as this can char the product and cause surface damage (Sheridan and Shilton, 1999). At high infrared heater temperature, the surface of the biological material loses moisture and fat, resulting in the formation of a crust.

Based on wavelength / temperature of emission, infrared energy can therefore be divided into three regions:

- Short wave or near infrared: 0.72 to 2 microns (3870 to 1180^oC)
- Medium wave or middle infrared: 2 to 4 microns (1180 to 450^oC)
- Long wave or far infrared: 4 to 1000 microns (<450^oC)

2.5.6 Microwave-Hot-Air Combination Drying

In recent years, microwave drying offered an alternative way to improve the quality of dehydrated products. Usually, drying is not induced by dielectric heating alone, but most microwave drying systems combine microwave and conventional heating. The heating may take place in separate operations or simultaneously. Microwave drying, like conventional drying, is caused by water vapor pressure differences between interior and surface regions, which provide a driving force for moisture transfer. It is most effective at product moistures below 20% (Mudgett, 1989). Therefore, essentially for economic reasons, it has been suggested that microwave energy should be applied in the falling rate period or at a low moisture content (where conventional drying takes a long time) to finish drying. And also because of the concentrated energy of a microwave system, only 20-35% of the floor space is required, as compared to conventional heating and drying equipment. However, Microwave drying has been used in drying of herbs (Giese, 1992), potato (Bouraout et al., 1994), raisins (Kostaropoulos and Sarvacos, 1995), apple and mushroom (Funebo and Ohlsson, 1998), diced apples (Feng and Tang, 1998), carrots (Prabhanjan et al, 1995; Litvin, Mannheim and Miltz, 1998; Lin, Durance and Scaman, 1998), blueberries (Ramaswamy and Nsonzi, 1998) and banana (Maskan, 2000). Microwave application has been reported to improve product quality such as better aroma, faster and better rehydration, considerable savings in energy and much shorter drying times compared with hot-air drying alone.

2.5.7 Microwave-Infrared Drying

Moisture accumulation at the food surface during microwave heating is a well-known problem. Crispy surfaces become soggy and surface color development, if desired, becomes difficult. Suggestions for the reduction of surface moisture often point to increasing the surface temperature by one of two ways - addition of an infrared source and/or hot air. Microwave-only heating results in surface moisture build-up due to enhanced (pressure-driven) flow of moisture to the surface and the cold ambient air's inability to remove moisture at a high rate.
When absorbed mostly on the surface, infrared can reduce surface moisture and, beyond a threshold power level, it can reduce the surface moisture to lower than its initial value. Hot air also can reduce surface moisture and increase surface temperature, but not as effectively as infrared heat, perhaps due to a much lower surface heat flux for hot air compared to the infrared energy.

2.5.8 Microwave-Vacuum Drying

Low boiling points are developed due to low pressures during microwave-vacuum dehydration, where the thermal damage was practically non-existent according to Erle and Schubert (2000). As long as there is enough water in the tissue, this boiling point can only be exceeded minimally due to dissolved substances.

2.5.9 Freeze Drying

Vacuum freeze-drying is the best method of water removal with final products of highest quality compared to other methods of food drying (Genin and Rene, 1995). Freeze drying is based on the dehydration by sublimation of a frozen product. Due to the absence of liquid water and low temperatures required for the process, rate of the deterioration and microbiological reactions would be very low which can gives a final product of excellent quality (Mui et al., 2002). The solid state of water during freeze-drying protects primary structure and the shape of the products with minimal reduction of volume. Despite of many advantages, freeze-drying has always been recognized as the most expensive process for manufacturing a dehydrated product.

A longer shelf-life, product diversity and substantial volume reduction are the reasons for popularity of dried fruits and vegetables, and this could be expanded further with improvements in product quality and process applications. These improvements in process selection could increase the current degree of acceptance of dehydrated foods in the market.

2.6 End-product Quality Analysis

Color and rehydration ratio are very important quality attributes of the dehydrated products. Processing steps such as slicing, cutting and drying always promote the color changes, which lead to reduction in visual and organoleptic quality of the dried product.

Rehydration ratio of the dehydrated product, i.e. the ratio of weight of processed food after rehydration to the weight of dehydrated processed food without water (g dehydrated product / g dehydrated product), can be determined as described by Ranganna (1986). The moisture content of both dehydrated and fresh berries can be determined by oven drying (AOAC, 1990).

2.7 Berry Drying Studies

According to Kostaropoulus and Saravacos (1995), Grabowski et al. (1992) and Masi and Riva (1988), the drying time of surface pretreated grapes (immersed in ethyl oleate, etc) was reduced by about half. Venkatachalapathy and Raghavan (1997) found a significant effect using a combination of ethyl oleate (3%) and NaOH (0.5%) for microwave drying of grapes. However, the convective drying rate of the strawberries was improved by only about 10% as a result of this pretreatment. In another study, surfactant pretreatment of basil leaves increased the drying rate by a factor of 14 (Rocha et al., 1993).

One of the most useful pretreatments for drying of fruit is osmotic dehydration (Beaudry, 2001). Osmotic dehydration is the incomplete removal of water from a food product by means of an osmotic agent (usually either sugar or salt solution). The main advantage of this process is its influence on the principal drying method, shortening of the drying process, resulting in lower energy requirements. Considering that heat is not applied in this stage, osmotic dehydration offers higher retention of initial food characteristics such as color, aroma, nutritional constituents and flavor compounds (Beaudry, 2001).

It was determined by Ponting and McBean (1970) that, for fruits with a waxy surface layer, the most effective treatment is with ethyl esters of fatty acids, especially oleic acid. Saravacos et al. (1988) and Tulasidas et al. (1993) used ethyl oleate (EO) as a pretreatment and found that it can improve the drying rate with only a minor effect on product quality. Beaudry (2001) tested different concentrations and time periods of dipping for cranberries and concluded that those have no significant influence on subsequent osmotic dehydration.

Harrington et al. (1978) found that application of ethyl oleate reduced the incidence of cracking in drying cherries and increased the drying rate. Rahman and Lamb (1991) and Rahman and Perera (1996) pretreated fresh cherry with different chemicals and reported ethyl oleate to be the best for drying as a pretreatment.

Tulasidas et al. (1993) reported that microwave convective combination drying could be used for drying grapes into high quality raisins at a considerably reduced drying time. Yang and Atallah (1985) studied the quality of intermediate moisture low bush blueberries by four methods and reported that microwave-assisted convection drying achieves the desired moisture level with in the least time. Reddy and Meda (2005) reported that drying of saskatoon berries in microwave-combination condition could be an effective preservation method for the short harvest seasoned fruit crop. Dielectric properties of saskatoon berries were measured to observe the effects of osmotic dehydration (Reddy et al., 2005) and reported that solute uptake due to osmotic dehydration increased dielectric loss factor values.

Yang et al. (1987) have studied the combined process of osmotic dehydration and freeze drying to produce a raisin type blueberry product and reported that the product exhibited good flavor, texture and overall quality and long shelf stability.

2.8 Summary of Chapter II

This chapter essentially summarized various topics and aspects related to:

- Production, physico-chemical characteristics study of saskatoon berries,
- Dielectric properties measurement principles and techniques,
- Chemical pretreatment for berries / fruits,
- Osmotic dehydration technique and effect on drying methods,
- Drying techniques for agri-food / high moisture plant materials, and
- Development of microwave-convection drying system.

CHAPTER III – MATERIALS AND METHODS

In this section, we explain the experimental plan, analytical techniques, modeling studies for drying data, end-product quality analysis and finally validate the data for statistical significance.

3.1. Experimental Plan and Procedure

To meet the proposed research objectives, research outlines stated in Figure 3.1 were followed in our experimental drying process. This involved procurement of North-line saskatoon berries of 2005 harvest, from a producer in Saskatoon region and storing them in the freezer (-15^{0}C).

Frozen Saskatoon Berries

↓

Chemical Pretreatment

↓

Osmotic Dehydration

↓

Microwave / Convection / Combination Drying

↓

End Product Quality Analysis

↓

Statistical Data Analysis

Figure 3.1 Stages of Saskatoon berry drying / dehydration process

Fresh berries were U-picked during the harvesting season. The next step was to chemically pre-treat the berries prior to osmotic dehydration to verify the effect of chemical pretreatment. Chemically pretreated berries were subjected to osmotic dehydration using two solutes of three different concentrations. As a standard practice for control treatment untreated berries were also used in the drying process. The important and final step of our experiments was drying of untreated and osmotic dehydration berries under microwave, convection and combination drying methods. A quality change due to drying was analyzed by measuring the color changes and rehydration-ratio after drying. All experiments were conducted during summer and winter 2005. These drying steps are detailed in the following sections of this chapter.

3.1.1 Chemical Pretreatment

To study the effect of chemical pretreatment on osmotic dehydration ethyl oleate mixture was used. Chemical pretreatment tests were performed using a solution of 2% ethyl oleate and 0.5% NaOH (mass basis) in distilled water. Liquid ethyl oleate was previously kept in a freezer at -20^{o}C, and granular NaOH at ambient temperature. After thawing, the berries were wiped with soft tissue and dipped into the prepared solution for different time period of 60,120 and 180 s separately. All experiments were done at room temperature (23^{0}C). The chemically pre-treated berries were then kept ready for osmotic dehydration experiments.

3.1.2 Osmotic Dehydration

Osmotic dehydration was carried out with two osmotic agents: sucrose (solution), commercially available fine granulated sugar with 99^{0} brix, and high fructose corn syrup (HFCS) of 70^{0} brix. The effect of these two osmotic agents with respect to dipping time was compared. Three concentration levels of sugar solution were used in this study to compare the effect of the concentration of the osmotic agents on osmotic dehydration. The sugar solution with 40, 50, and 60^0 brix concentration were prepared and the chemically treated and untreated (thawed but without treated with chemicals) saskatoon berries were immersed in the osmotic reagents for a duration 6, 12, 18, 24 and 36 h, respectively.

Optimal chemical and mechanical pretreatments were determined, different factors of osmotic dehydration were tested. These factors and their levels were studied as below:

- Type of Sugar agent (Crystal sucrose and Liquid High Fructose Corn Syrup)
- Concentration of sugar agent (40, 50 and 60^0 brix)
- Time of osmotic dehydration (6,12, 18, 24 and 36 h)

Different concentrations of sugar solutions were prepared and equivalent weight of berries were added. The solution was mixed and known weights of berries were collected after every 6 h and washed with tap water to remove the solute on the berry surface during each sampling.
For simplification, only two counter-diffusions are usually assumed to take place in osmotic dehydration process, with one being the water diffusing out from the inner cell to the surrounding solution and the other being the solute diffusing from the surrounding solution into the cell. Water Loss (WL, kg/kg fresh material) and Solute Gain (SG, kg/kg fresh material) are two main parameters to consider in this process. Both diffusion processes are interdependent.

3.1.3 Saskatoon Berry Drying

Drying is an important step in the preservation of saskatoon berries, to reduce the M.C. from 75% (60% after osmotic dehydration) to 25% (or lower) in a very short time after harvest. The experiments conducted under different drying conditions are listed in Table 3.1.

The following parameters were measured and maintained in our experiments:

- Product temperature: 60, 70, and 80^{0}C (Microwave power levels: P1, P2 and P3),
- Airflow rate: 1 to 1.4 m/s,
- Relative humidity: 14-18%, and
- Final moisture content: 25%

Table 3.1 Experimental design indicating various treatments, drying modes and power levels.

Pre-treatment Condition	**Microwave**			**Combination (MW + Convection)**			**Convection**		
	P1	**P2**	**P3**	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
60% Sucrose (24H)	3	3	3	3	3	3	3	3	3
60% HFCS (24H)	3	3	3	3	3	3	3	3	3
Untreated	3	3	3	3	3	3	3	3	3

Note: Convection air temperatures were higher (15^{0}C) to maintain product temperatures of 60, 70, and 80^{0}C.

3.1.4 Microwave and Microwave-Convection Drying

For all the microwave and microwave combination drying studies, a Panasonic Microwave-Convection oven NNC980W (Panasonic Canada Ltd, Ontario Canada) that was developed into a stand-alone drying system was used. The dryer system features and modifications are detailed in Chapter IV (Development of dryer).

3.1.5 Convection Drying

For convection-only drying, a cross flow dryer in the bioprocessing laboratory that was developed for thin layer drying of both high and low moisture agricultural materials (Adapa et al., 2002) was successfully used. This dryer had the following features and capabilities:

- Convection air temperature from 25 to 150^{0}C,
- Relative humidity adjustment from 5 to 75%,
- Airflow rate from 0 to 2 m/s,
- Measurement of air (T-type thermocouples) and product temperatures (Infrared sensor),
- Online moisture loss measurement, and
- Ability to record moisture loss, air temperature, product temperature, air flow rate, and relative humidity during drying using a computer with LabView 6i data acquisition software.

3.2 Analytical Procedures

3.2.1 Berry Sample Preparation

Frozen berries (North line variety) of 2004/05-harvest season were procured from Riverbend Plantations, Saskatoon. Prior to all experiments, frozen berries were taken out of cold storage and thawed at room temperature for 2 h, until the produce temperature was equilibrated. Initial moisture content and total soluble solids (TSS) content were 76% and 15.8^0 brix, respectively. Prior to individual drying experiments, the whole fruit samples were taken out of cold storage and thawed for 2 h. The moisture content of each sample was measured individually.

3.2.2 Moisture Content Determination

Saskatoon berry samples of 5 g were dried in a vacuum oven at 70^{0}C and 25 psi for 7 h to assess their initial moisture contents. This experiment was carried out in three replicates. The initial moisture content (MC) of the saskatoon berries was determined as 76% dry basis (d.b.) according to AOAC Standards (1990).

3.2.3 Total Soluble Solids (TSS) Measurement

Saskatoon berries were manually crushed and the fruit syrup was extracted through cheesecloth. Digital hand held pocket Refractometer (PAL-1, 0-53^0 brix, and PAL-2,50-93^0 brix, ATAGO Co. Ltd, Japan) was used to determine the brix level of the fruit syrup. PAL-1 had a measuring range of 0 to 53^o brix and PAL-2 from 53 to 95^0 brix. For all measurements, 0.3 ml of the fruit extract sample was used.

3.2.4 Dielectric Properties Measurement and Sample Preparation

In order to better understand the interaction of microwave and fruit samples, the dielectric properties measurement was necessary. Also, from modeling point of view this information might be useful. Measurement of the dielectric properties was performed with an open-ended coaxial probe connected to HP 8510B Network Analyzer setup in bioprocessing laboratory. The analyzer generates a microwave signal through the coaxial probes. The material is tested by bringing in contact the flat surface of the probe with the material under test. The fields at the end of the probe "fringe" into the material and change as they come in contact with the material. The network analyzer detects the magnitude and phase shift of the reflected signal and calculates the reflection coefficient. Then graphically computer controlled software calculates the dielectric properties from these data and displays it as a function of frequency.

The coaxial probe (Figure 3.2) is a convenient and broadband technique for lossy (materials with high dielectric loss factor values) liquids and solids. It is non-destructive and little or no sample preparation is required for liquids or semi-solids. In the case of a solid material under test, the material face must be machined at least as flat as a probe face, as any air gap can be a significant source of error. It operates at frequencies between 0.045 and 26.5 GHz. The technique assumes the material under test to be non-magnetic and uniform throughout.

The HP 8510 is a high performance microwave Vector Network Analyzer (VNA) system. It consists of a HP 8510B, a Test Set (e.g. HP8515A S-Parameter Test Set), and a Microwave Signal Source (HP 8341B). This Agilent VEE (Vector network analyzer driver) controls the HP 8510 "system" as a whole. That is, commands issued through the HP 8510 driver also control the test set and the signal source. The open–ended coaxial probe technique was used to measure dielectric properties of grain samples.

This method was selected for the following reasons:

- It allows simple sample measurement and data analysis,
- The instrumentation is commercially available, and
- Dielectric properties can be obtained over a wide frequency range in a single measurement and with adequate accuracy for thermal calculations (Engelder and Buffler, 1991).

An HP software program provided the permittivity based on the measured reflection coefficient (Engelder and Buffler, 1991). For coaxial probe measurements, the HP dielectric probe kit (HP 8510B) is utilized, which consists of the probe, related software, and calibration standards. The calibration consists of measuring three known standards with the probe (usually open air, short block, and distilled water at room temperature). The calibration process removes systematic errors from the measurement. The operating frequency range of the system was set to 0.5 MHz to 5 GHz. All the measurements were taken at room temperature (23^0C) and constant bulk density. The menu driven software was installed on the personal computer and the control algorithm based software computes the complex permittivity of the material under test from the S-parameter information, which was relayed from the vector network analyzer (VNA).

To reduce cable flexure and probe motion errors during measurements, a fixture was developed which securely clamps the probe and its cable in a vertical position (as shown in Figure 3.2). The fixture is equipped with a small table on which the calibration standard or material under test is placed. This table is mounted to a manually operated vertical position translator, which allows the operator to raise the material under test up to the probe tip with high positional precision and with the proper contact pressure.

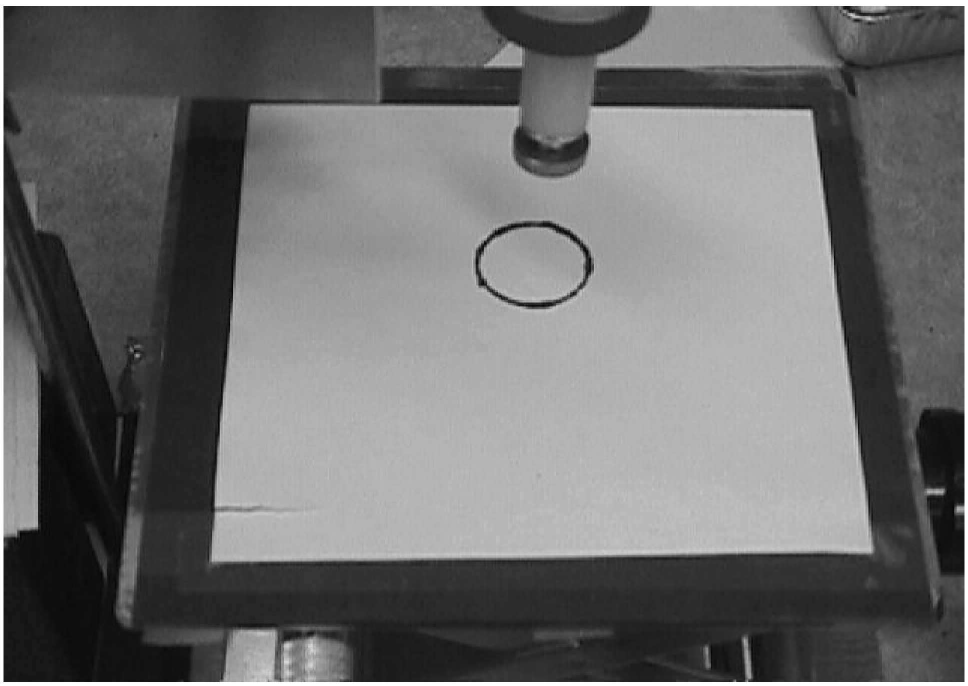

Figure 3.2 Open-ended coaxial probe and adjustable platform

All dielectric measurements were performed at room temperature (23^0C). Measurements for dielectric properties were performed using the HP Network analyzer system on fresh and frozen saskatoon berries for the following different fruit conditions:

- Whole berry,
- Cut berry,
- Berry paste, and

- Berry juice / Syrup

Osmotic dehydration process that involves loss of moisture and solid gain can affect the dielectric properties of the fruit. As the drying experiments involved drying of untreated and osmotically dehydrated saskatoon berries under microwave conditions, measurement of dielectric properties before and after osmotic dehydration revealed the effect of osmotic dehydration on drying characteristics and microwave absorption characteristics of the material.

3.3 Dehydrated Product Quality Analysis

Quality analysis by measuring color changes and rehydration ratio were carried out to explain the effect of the drying process and conditions on final dried product.

3.3.1 Color Measurements

The color measurements were done using Hunterlab Color Analyzer (Hunter Associates Laboratory Inc., Reston, Virginia, U.S.A.). The chromacity of convection, microwave and microwave combination dried berries was determined by measuring their respective L, a and b coordinates. After initial calibration against standard white and black surface plates, three replication measurements for each sample were taken. L being the lightness indicator and a and b are the chromacity coordinates. Color difference values ΔL, Δa and Δb were calculated according to the following equations:

$$\Delta L = L - L_t \quad (3.2)$$

$$\Delta a = a - a_t \quad (3.3)$$

$$\Delta b = b - b_t \quad (3.4)$$

Where L, a and b are the measured values of the specimen and L_t, a_t, b_t are values of the target color. The target colors in this experiment are L, a and b of the fresh saskatoon berry fruit. The total color difference ΔE_{ab} is measured using the L, a, b color coordinates and as defined by the Equation 3.5 (Minolta, 1991):

$$\Delta E_{ab} = [(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2]^{0.5} \qquad (3.5)$$

3.3.2 Rehydration Test

Rehydration tests of dried samples were performed by the method recommended by Annon (1991). A sample of the dry material was weighed into a 500 ml beaker containing 150 ml of distilled water. The beaker was placed on a hot plate and covered with a watch glass, the water was brought to the boiling point in 3 min and sample was added to the boiling water and boiled for an additional 5 min. The sample was transferred to a 7.5 cm Buchner funnel covered with Whatman No. 4 filter paper. Water was drained out until there were no more drops from the funnel. The sample was then removed and weighed. Rehydration ratio was calculated as the ratio of mass of rehydrated sample to that of the dehydrated sample. The coefficient of rehydration (COR) is calculated by equation 3.6.

$$COR = \frac{M_{rh}\,(100 - M_{in})}{M_{dh}(100 - M_{fn})} \qquad (3.6)$$

Where,

COR = Coefficient of rehydration,

M_{rh} = Mass of rehydrated sample (g),

M_{dh} = Mass of dehydrated sample (g),

M_{in} = Initial moisture content of the sample before drying (%), and

M_{fn} = moisture content of the dry sample (%).

3.3.3 Micro-structural Analysis

The Phillips Scanning Electron Microscope (SEM 505, Phillips, Holland Electrons Optics, Eindhoven, and Netherland) was used to visualize the microstructure of the samples and study specimens that require higher magnifications and greater depths of field that can be attained optically. Saskatoon berries were observed for physical changes that occurred after osmotic dehydration treatment and drying experiments. The digital image of scanning electron microscope equipment is shown in Figure 3.3.

Samples were prepared in the following manner. The samples were kept free from moisture and other contaminants as possible and then they were pinned down to a sample holder using a conductive carbon tape that contained adhesive on both the sides. The samples were first dried in vacuum drier at 1080 pascals pressure and 31.5^{0}C. With the sample conductively tied to the holder, a non-conducting sample needs to go through one more preparation step.

Figure 3.3 Photograph of SEM system with computer

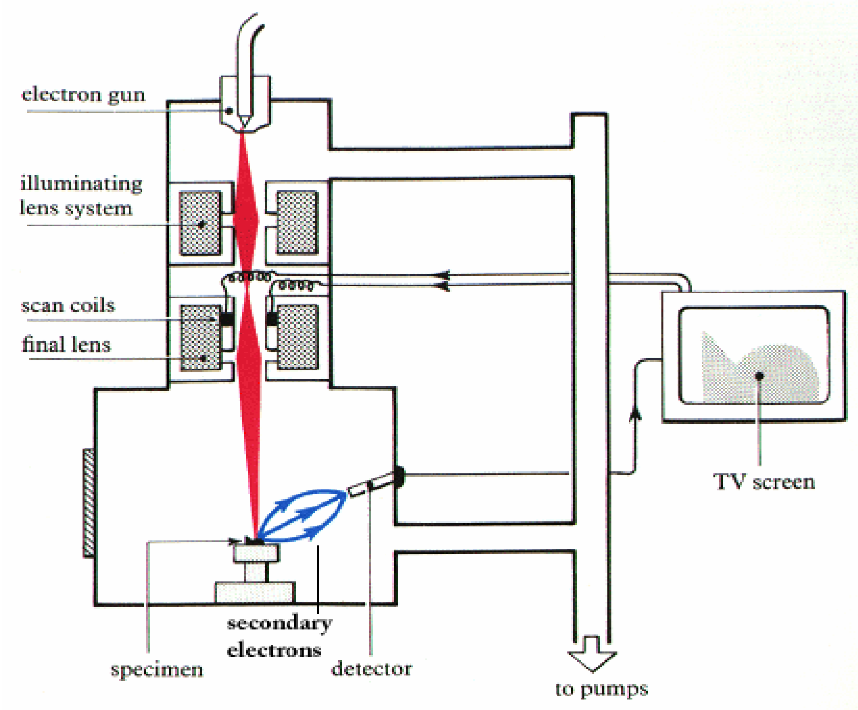

Figure 3.4 Functional components and operating principle of Scanning Electron Microscope (SEM)

3.4 Modeling of Drying Process

Many researchers have adopted empirical models due to the consideration for simplicity and accuracy. The simple type of drying model assumes that rate of exchange in moisture content is proportional to the difference between moisture content and Equilibrium Moisture Content (EMC) of the material. This section deals with five identified drying modes reported in the literature and adapted to our work.

3.4.1 Moisture Ratio Determination

Moisture ratio was determined in order to compare each set of data, e.g., berries at 60^0C and different drying treatments (microwave, convection and combination). Moisture ratio was calculated using following equation:

$$MR = \frac{M - M_e}{M_i - M_e} \quad (3.7)$$

Where,

MR = Moisture Ratio,

M = Average moisture content, % (d.b. at drying time t),

M_i = Initial moisture content, % (d.b.), and

M_e = EMC, % (d.b.).

Based on extensive review of literature, the drying models listed in Table 3.2 were developed and adapted for our research. The moisture content data at different microwave, combination and Convection temperature (power levels) were fitted against drying time, using the various models given in Table 3.2.

Table 3.2 Drying models fitted for the drying data

Model No.	Name	Drying Models	References
1	Page Eqn.	$MR=\exp(-k\,t^n)$	Liu and Bakker-Arkema (1997)
2	Modified Drying Eqn.	$MR=a+\exp(-k\,t^n)$	Agrawal and Singh (1977)
3	Wang and Singh	$MR=1+at+bt^2$	Wang and Singh (1978)
4	Sharma et al.	$MR=a*\exp(-bt)+c*\exp(-dt)$	Sharma et al. (2005)
5	Midilli Equation	$MR=a*\exp(-k(tn))+b*t$	Midilli et al. (2002)

Where,

MR = Moisture Ratio (Equation 3.7),

k = Drying constant, min^{-1}

t = Drying time, min

a, b, c, and d = Constants

3.5 Statistical Analysis

3.5.1 Chemical Pretreatment

One-way ANOVA was performed to verify if there was significant difference in solute uptake between control treatment and 3 chemical pre-treatment levels.
Factors for analysis were:

- 1 control treatment – Untreated berries
- 3 treatments – 60, 120 and 180 s chemical pretreatment duration
- 3 replications

3.5.2 Osmotic Dehydration

Three-factor Randomized Complete Block Design (RCBD) was used to verify the effect of solutes, solute concentrations and time effect on solute uptake and mass loss.

RCBD: After the experimental units are blocked, treatments are assigned at random within each block such that each treatment occurs once in every block. During the conduct of the experiment where the order of processing the material may make a difference, units are processed by block and in a completely random order within each block.

Model for RCBD is shown below:

$$Y_{ij} = \mu + \tau_i + \beta_j + \varepsilon_{ij} \tag{3.8}$$

Where,

Y_{ij} = Observed value for the j^{th} replicate of the i^{th} treatment (where i=1 to t and j=1 to b),

μ = Grand mean,

τ_i = Treatment effect for the i^{th} treatment; the treatment effects may be either fixed or random,

β_j = Block effect for the j^{th} block, and

ε_{ij} = Random error associated with the Y_{ij} experimental unit.

For osmotic dehydration there were 3 treatments (i=3) and 3 replications (j=3).

The treatments were:

- Solutes – sucrose and high fructose corn syrup,
- Solute concentrations - 40, 50, and 60%, and
- Time - 6, 12, 18, 24, and 36 h.

3.5.3 Drying Experiments

Two-factor RCBD was used to verify the effect of 2 treatments and 3 replications on drying time.

The treatments were:

- Drying modes – microwave, microwave-convection, and convection drying, and
- Power level – 3 levels (60, 70 and 80^0C product temperatures).

Chapter IV – DEVELOPMENT OF A MICROWAVE DRYER SYSTEM

For this research study, dryer development was a major contribution and majority of the research time and effort was dedicated for the equipment modifications, installation of sensors, tools, data acquisition system and other accessories to modify domestic microwave-convection oven into a laboratory scale microwave-convection combination dryer system. This section explains the above mentioned points in detail. Modification of the oven with necessary instrumentation and installation of measurement systems (temperature, weight-loss, etc) along with data acquisition system capabilities were carried out.

4.1. Configuration of Microwave-Convection Oven

A commercially available Microwave-convection oven Panasonic (NNC980W) (Panasonic Canada Ltd, Ontario Canada) was used for development into a stand-alone drying system. The system controls the microwave power output in continuous mode rather than as a duty cycle. The dimensions of the cavity were 0.24 x 0.41 x 0.42 m. From the ceiling of the oven cavity, a blower fan forced the preheated air through a meshed inlet into the cavity. A pair of electrical heaters of 1400 W capacity was controlled by a variable transformer in order to supply heated air at required temperature levels.

The following design and operating features were built-in with a commercial oven:

- 10 different modes of microwave power (220 – 1000 W),
- Inverter technology for variation of microwave power,
- The dimensions of the cavity are 0.24 x 0.41 x 0.42 m,
- Convection / Hot-air (1400 W) stream which operated independently and also in combination with microwave at two set-point convection temperatures,

- Convection fan running with a 12 V input voltage and a maximum air flow rate of 1.5 m/s, and
- Humidity sensor at the outlet of convective air from the dryer system.

The following system modifications were identified to be developed into an integrated combination dryer system:

- Separate controls for microwave and convection air,
- Temperature controller installation for convection air and fan control,
- Inserting fibre optic probes into the oven and making arrangements for online temperature measurement using fibre optic sensors and record the data using LabView 6i software,
- Sample holder design to dry approximately 100 g of berries, and
- Weighing the sample during drying to measure the real-time moisture loss and record the data using LabView software.

4.2. Microwave and Convection System Instrumentation

There was an option to toggle between preset system conditions and modified settings. Following were the preset settings:

- Microwave control was from the front panel (set different power levels and time) both in manual and automatic manner,
- A second panel; convection panel in Figure 4.1, was integrated to the system having two stopwatches, one for convection and the other one for microwave. One digital counter with display was added to this circuitry to count the number of times toggling between microwave and convection, and
- Convection fan operation during convection / combination / manual mode was continuous.

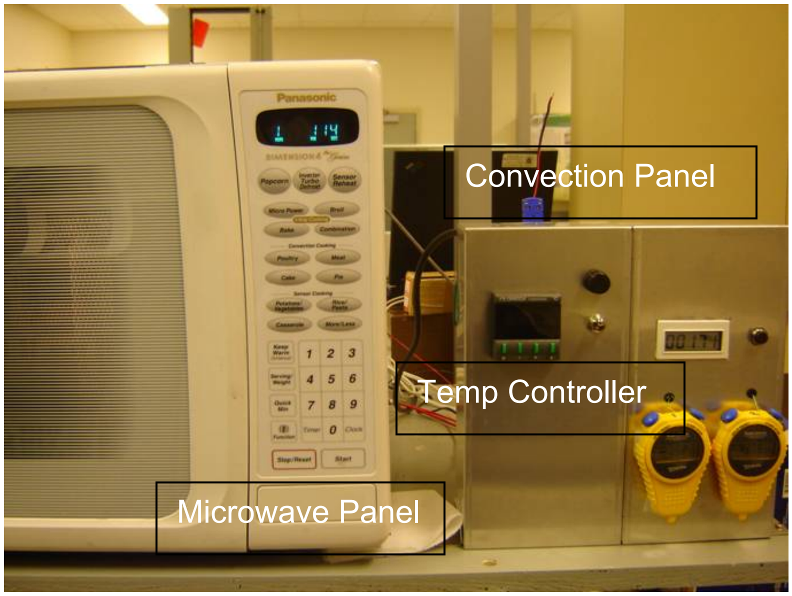

Figure 4.1 Front panels of the microwave drying system (left panel to set microwave power and run-time and right panel to set and monitor convection temperatures)

4.3. Convection Air Temperature Controller Installation

In manual control setting for convection air temperature adjustment and control, an OMEGA CN9000A temperature controller was installed (Figure 4.1). In this temperature controller, a set point for temperature setting temperature from room temperature to 150^{0}C. Once the set point temperature was reached, a solid-state relay (SSR) circuit switched off the connection stream, which was in connection with the temperature controller and heater filament system.

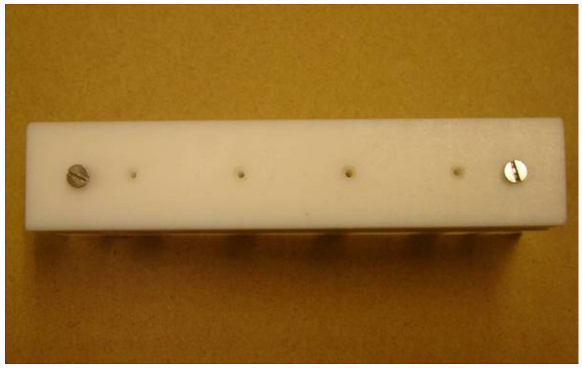

Figure 4.2 Teflon block fabricated to insert fibre optic temperature probes in to the microwave cavity

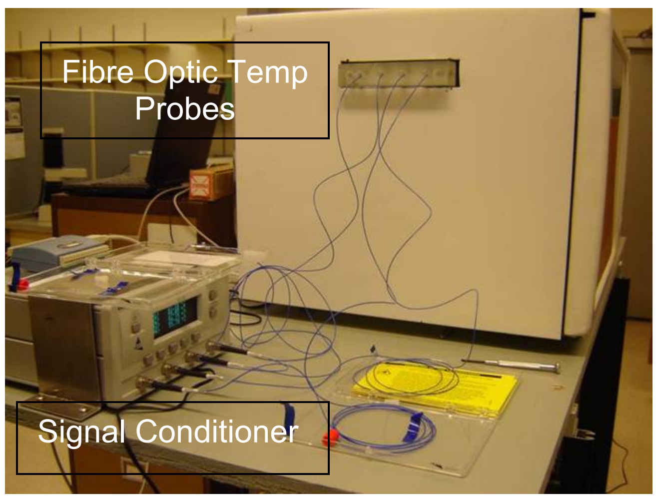

Figure 4.3 An assembly of fibre optic temperature sensors and signal conditioner for temperature measurement

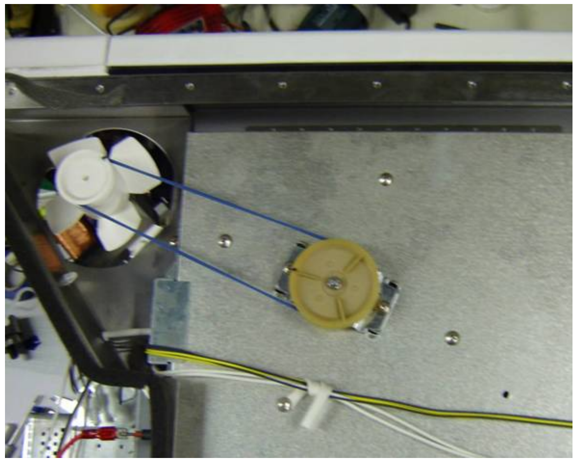

Figure 4.4 Aerial view of the convection fan and the belt pulley arrangement

Based on the set of preliminary experiments, it was observed that the voltage supply to the heater was of 1400 W (maximum) all the time. The fan and heater units switched off automatically when the set point temperature was reached. This was not a favorable condition in continuous drying systems where fan must be running all the time to maintain constant airflow rate. To overcome this problem, a rheostat and voltmeter in series with temperature controller was set-up. By varying the rheostat the resistance varied in the circuit causing a change in voltage supply to the heater that was displayed on the voltmeter. This circuit helped to supply a known voltage to the heater to attain the set point temperature and maintain the same throughout. Convection fan was supplied with constant voltage of 12 V to run continuously even when the heater went off maintaining a constant airflow rate.

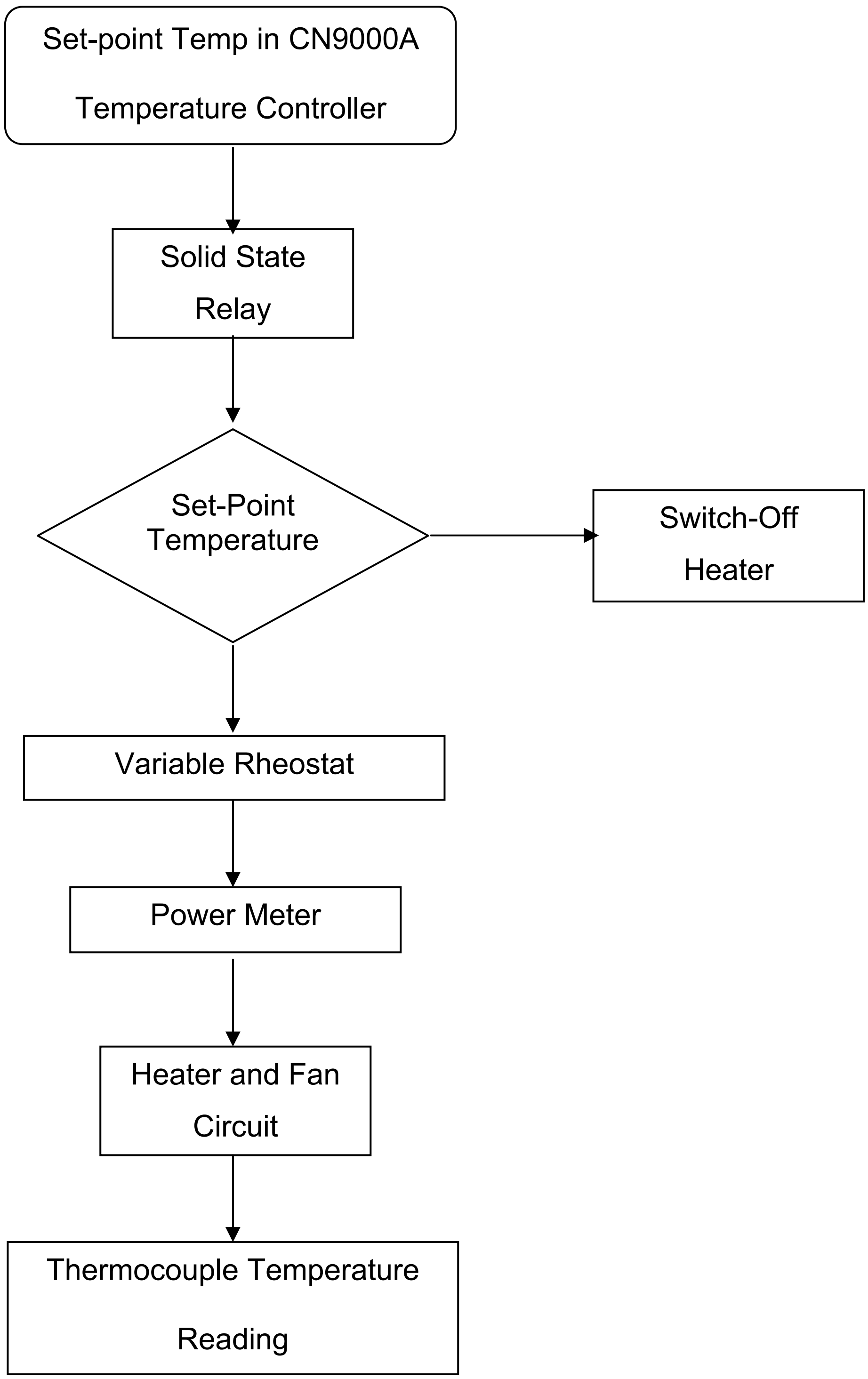

Figure 4.5 Flowchart of the convection heating system explaining the working operation of the convection heating circuit

4.3.1 Airflow Rate Measurement

Airflow rate measurement was carried out using a hot-wire anemometer at different spots in the microwave chamber. Airflow variation at the sample holder position was 1 ± 0.1 m/s around the sample holder location.

4.4 Data Acquisition Module Integration

Data acquisitions for temperature and weight loss were performed simultaneously during drying using an IBM laptop (Pentium II) with programs written in LabView 6i.

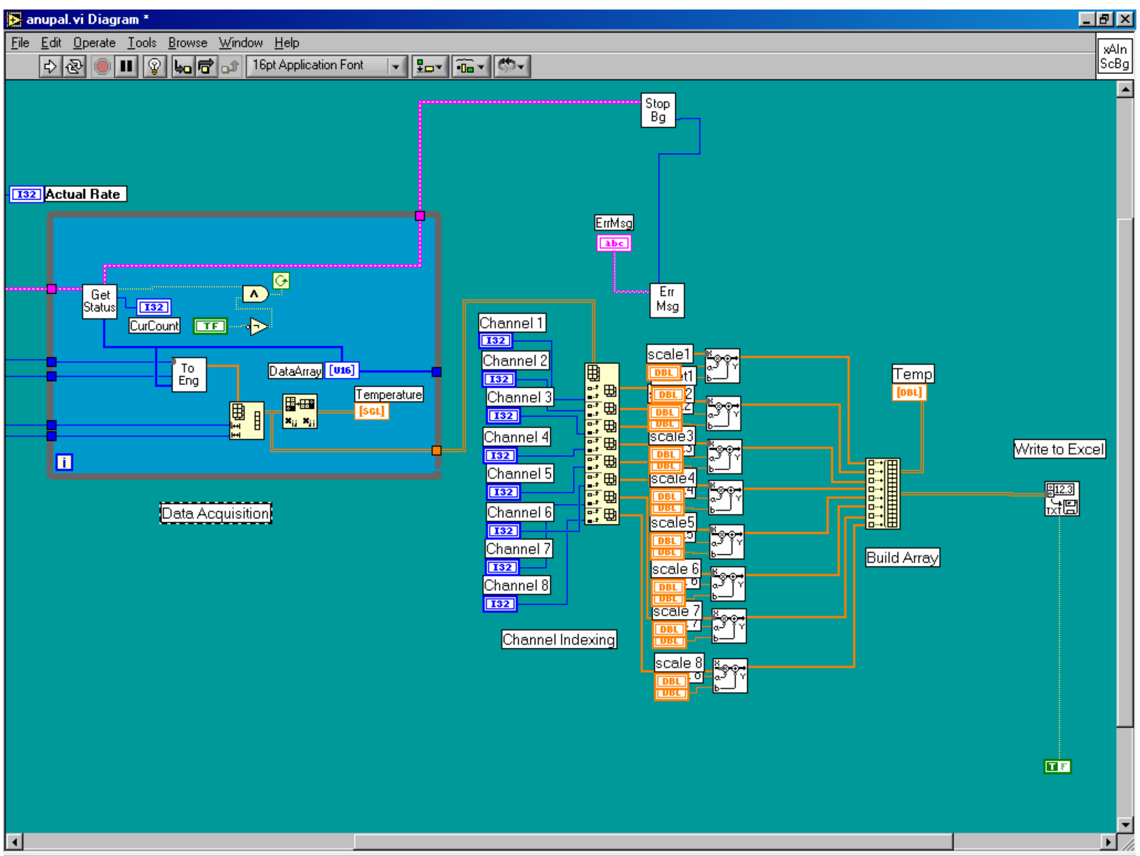

Figure 4.6 Temperature data acquisition flowchart explaining the step-by-step procedure adapted in temperature data acquisition

4.4.1. Temperature Data Acquisition

The Fiso four channel sensor and signal conditioner (UMI 250, Fiso Canada, -50 to 250^{0}C, 0.01^{0}C accuracy) to computer modules are a family of complete solutions designed for data acquisition systems based on personal computers and other process based equipment's with standards I/O ports.

The module converts four analog input signals to engineering units (shown in Figure 4.6 and Figure 4.7) and transmits in ASCII format to any host with standard RS-485 or 232C ports. The maximum number of channels for temperature measurement was limited to four. The unit was interfaced to a personal computer via an RS 232 serial port or USB post from the DAQ card.

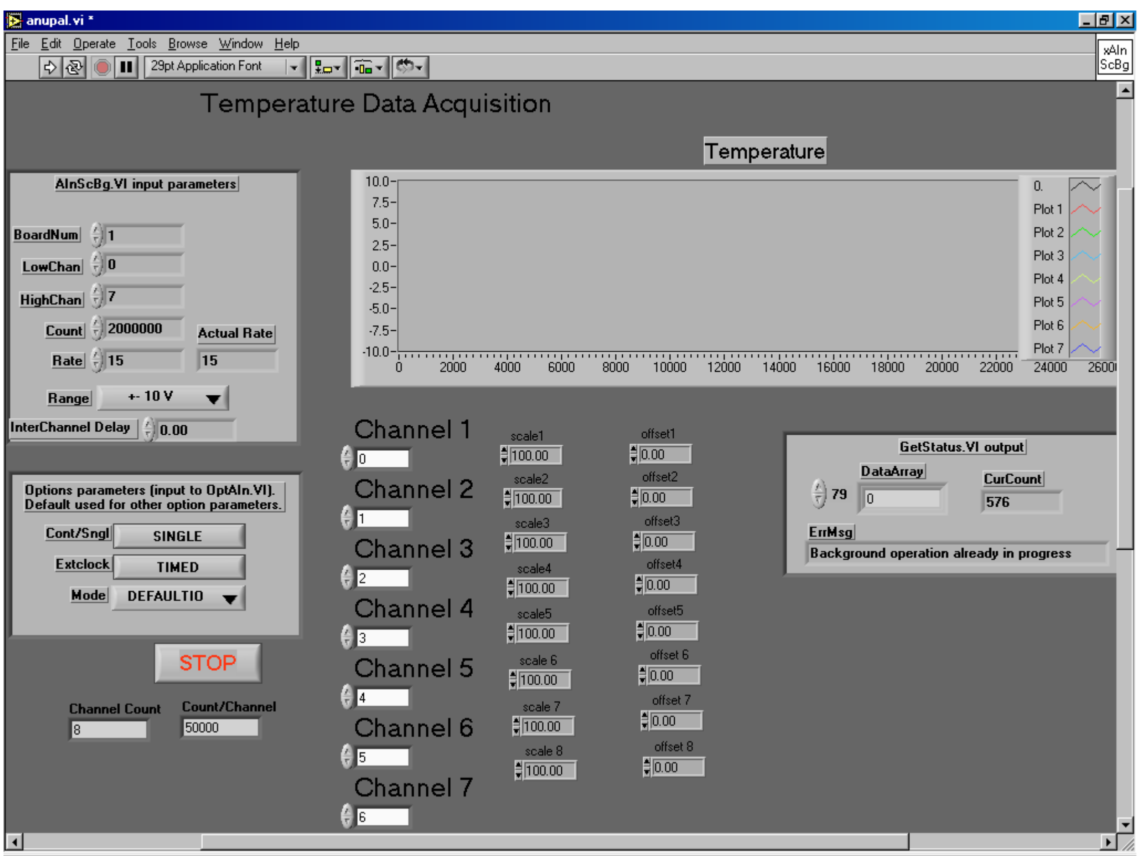

Figure 4.7 Temperature data acquisition main screen of LabView 6i program

4.4.2. Data Acquisition Software

In order to get continuous temperature time data LabView 6i module software was used for data acquisition. Data acquisition hardware was connected to LabView through the Fiso UMI Signal conditioner module for temperature data and through serial I/O port for weight loss data.

4.4.3. Online Weight-Loss Measurement

Ohaus Adventurer (Ohaus, Ontario, Canada, 2004, 0.1g accuracy) 800 g balance was mounted on top of the microwave oven and a sample holder specifically designed for drying of 100 g of sample, made of polycarbonate, was hooked on to the balance hook located below that read data.

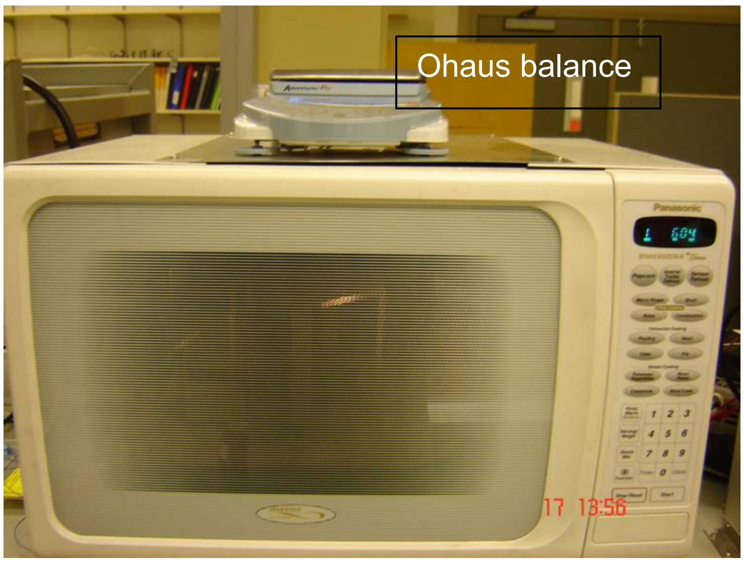

Figure 4.8 Ohaus balance mounted on top of the microwave system to record online weight loss data

This scale was connected to the laptop computer via Serial I/O post to record the data at specific intervals using serial communication VI (LabView software program) and finally written onto a Microsoft Excel (2003). There was slight variation in the data acquisition pattern due to convective air movement.

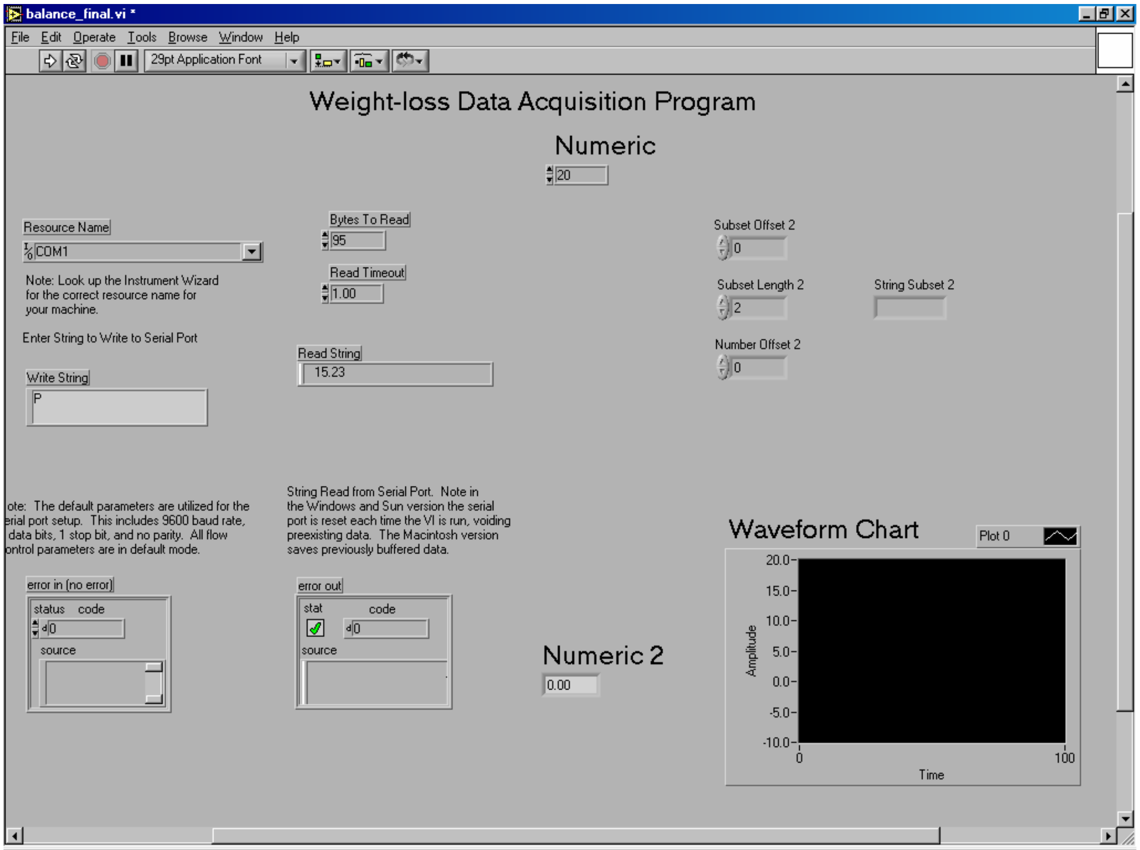

Figure 4.9 Weight-loss data acquisition flowchart indicating the step-by-step procedure adapted in temperature data acquisition

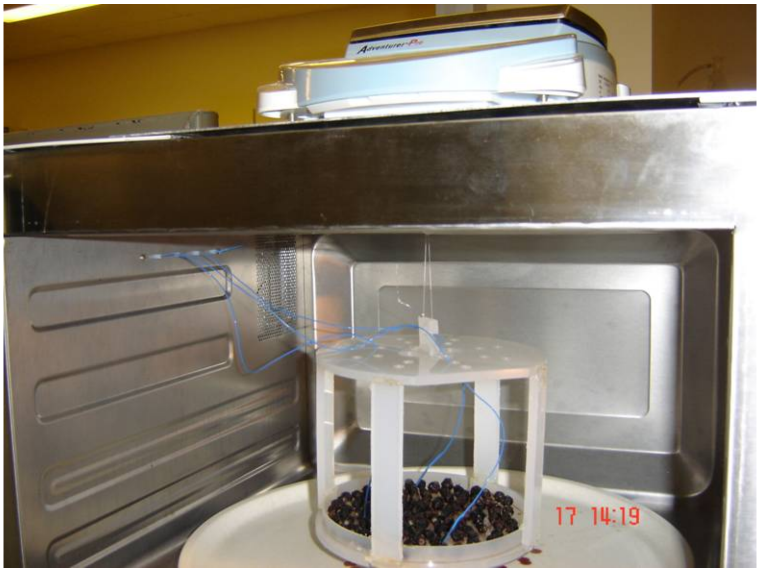

Figure 4.10 Sample holder connected to a weighing scale by nylon string

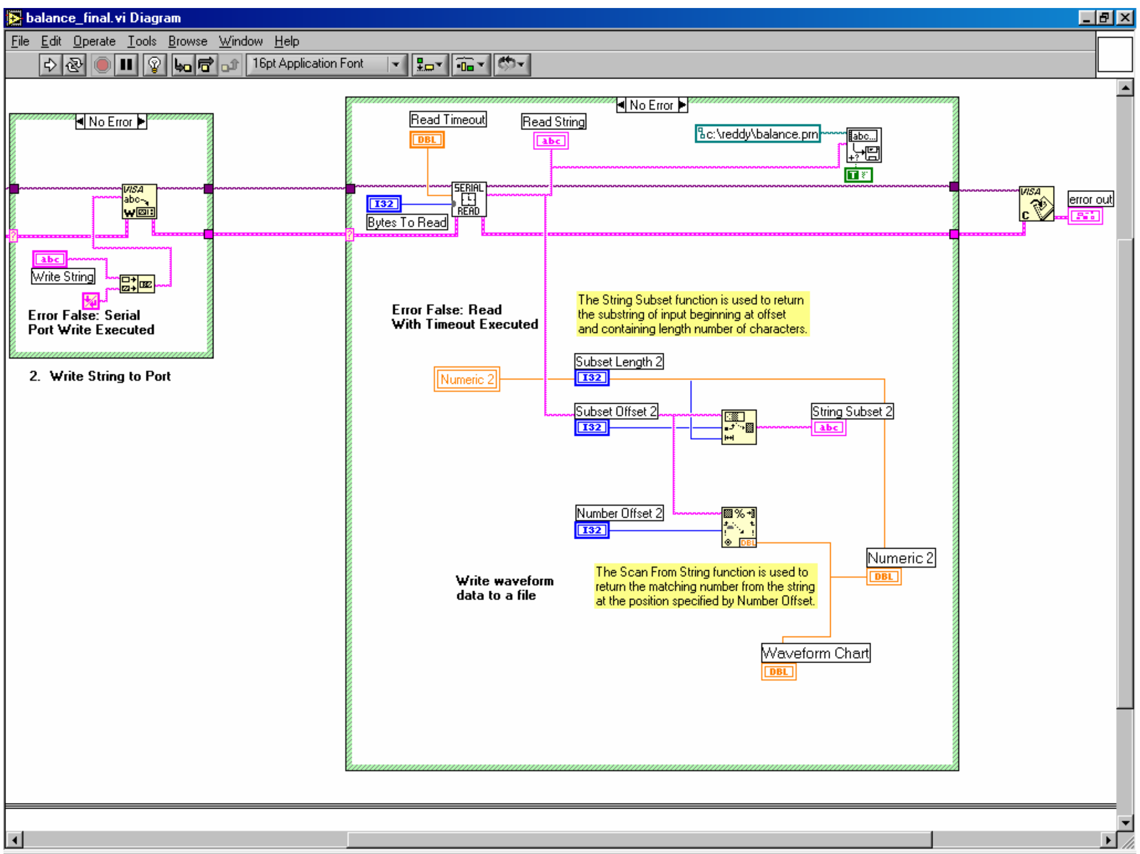

Figure 4.11 Weight-loss data acquisition snap-shot of LabView program

Figure 4.12 Sample holder with saskatoon berry dried samples with temperature sensors

4.4.3.1. Weight-loss Calibration

Airflow movement surrounding the sample holder would cause change in weight measurement. To overcome this problem, the Ohaus balance was calibrated to acquire data after the sample holder stabilized with the air movement. Berries of known quantity (100 g) were placed in the sample holder with convection air flow. LabView program acquired data on the laptop and this weight was berry weight with error factor due to air movement. Final weight of the berries was predetermined and it was possible to calculate actual berry weight by deducting the error factor value.

4.5. Standard Reference Material (Water) Testing

The measurement of power output of the microwave oven was determined calorimetrically (Khraisheh et al., 1997) i.e. the change of temperature of a known mass of water for a known period of time. The basic equation is:

$$\mathrm{MW_{abs}} = \frac{(4.187 mCp\Delta T)}{\Delta t} \tag{4.1}$$

Where,

MW_{abs} = power absorbed by the sample (W),

m = Mass of sample (g),

Cp = Specific heat of the material (kJ/kg-C),

ΔT = Temperature rise in the water load (^{o}C), and

Δt = Heating Time (s).

Table 4.1 Measured output power of the microwave system

POWER LEVEL (Settings in Microwave)	MEASURED POWER (Watts)
P10	1000
P9	751
P8	682
P7	689
P6	628
P5	500
P4	392
P3	295
P2 (Pulsating)	295 (7 sec off and 14 sec on)
P1 (Pulsating)	295 (14 sec off and 7 sec on)

Water into two one-liter beakers weighing 2,000 ± 5 g were placed in the center of the oven, side-by-side in the width dimension of the cavity, and touching each other. The beakers initially should be at ambient room temperature and the initial water temperature should be 20°C ± 2°C (Buffler, 1993). The oven was run at all inbuilt microwave power levels for 2 min and 2 s, the beakers were removed and the final temperatures recorded. Absorbed power is calculated from a simplified formula of Equation (4.1):

$$P = 35 \times (\Delta T_1 + \Delta T_2) \tag{4.2}$$

Where,

$\Delta T1$ and $\Delta T2$ are the temperature increases of the water in the two beakers (^oC).

Power measurement was repeated for three times, with the final oven power being the average of the three readings (Table 4.1). If any individual measurement was more than 5% away from the average, the complete test was repeated.

NOTE: The water in each vessel should be well stirred before measuring both the starting and final temperature. A small object, such as a plastic spoon or the handle of a wooden spoon works well.

4.6 Summary of Chapter IV

An existing domestic microwave oven developed into an integrated laboratory-scale drying system. The following lists the specifications of the developed functional system:

- System Feasibility – The developed drying system can be used for drying of varied agricultural / food materials under microwave, convection and microwave-convection combination drying conditions,
- Microwave Power Control – Different output power levels of microwave can be selected depending on the power requirement to dry a product,
- Convection Power Control – Output temperatures in the oven can be set in the temperature controller (room temperature to 200^oC) that is maintained by the variable rheostat and the solid-state relay circuit,
- Temperature Measurement – Installed fibre optic temperature probes with signal conditioner will measure online product and the drying environment temperature that is recorded on the laptop with a LabView program, and

- Weight Measurement – Weighing scale mounted on top of the oven was connected to the sample holder that acquired product weight loss data online and this data was transferred to the laptop (connected through serial port) with LabView program.

CHAPTER V – RESULTS AND DISCUSSION

In this chapter, drying experiments results obtained using the developed laboratory-scale microwave drying system (discussed in detail in Chapter IV) will be explained. Data obtained from chemical pre-treatment, dielectric properties measurement, osmotic dehydration and final-drying experiments will be presented with statistical analysis.

5.1. Chemical Pre-treatment Experiments

To assess the effect of ethyl esters (ethyl oleate) and NaOH on osmotic dehydration (OD), untreated sample brix (TSS) measurement was used as a control, as explained in Chapter 2.2.3.

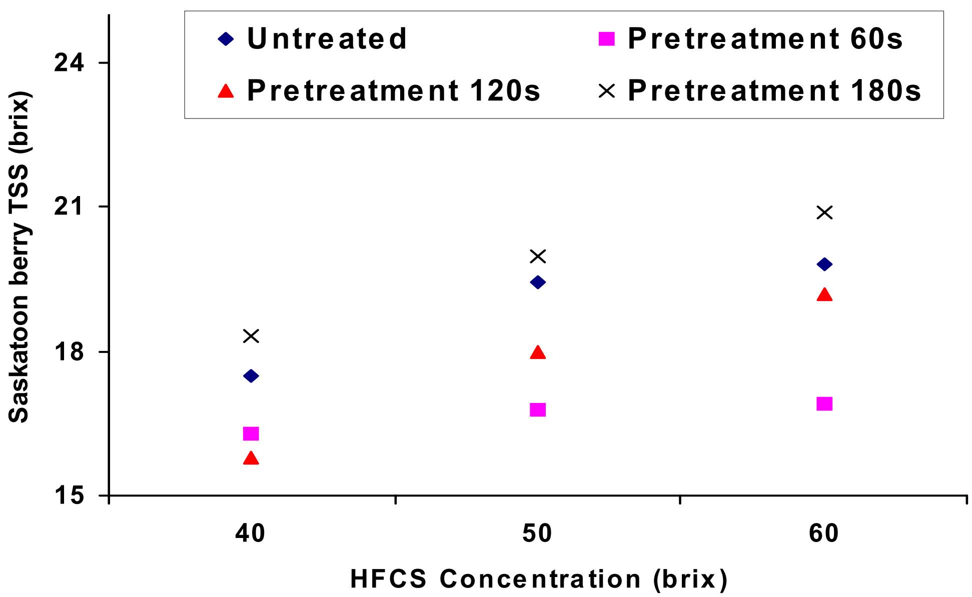

Figure 5.1 Saskatoon berries brix levels (TSS) after Chemical Pre-treatment and 6 h Osmotic Dehydration with high fructose corn syrup

Another factor to assess the effect of chemical pre-treatment was by observing the berry surface under a scanning electron microscope (before and after treatment) for any physical changes that might occur on the fruit surface (waxy layer / epithelial tissues) of fresh and chemically pre-treated osmotically dehydrated berries. Figure 5.1 shows different sugar concentration (40, 50 and 60%) effect on untreated and chemically pre-treated berries for 60, 120 and 180 after 6h of osmotic dehydration. The solute gain increases with increase of sugar concentration of the solution; fruit brix of untreated berries is higher than pre-treated samples. Pre-treatment after 180 s showed higher brix values for all three-sugar concentrations. One-way ANOVA on the results shows chemical pre-treatment had no significant (P=0.753) effect on osmotic dehydration process on saskatoon berries. Data for both high fructose corn syrup and sucrose osmotic dehydration results is presented in Table 5.1.

Table 5.1 Moisture content and Total soluble solids of osmotic dehydrated berries after chemical pre-treatment

Osmotic Agent	**Chemical pre-treatment (sec)**	**Sugar Content (Brix)**		**Moisture Content (% wb)**	
	Treatment	**Final**	**Initial**	**Initial**	**Final**
Sucrose	(P1)60	19.1	15.8	76	73.1
	(P2)120	18.6	15.8	76	74
	(P3)180	20.2	15.8	76	73
HFCS	(P1) 60	16.9	15.8	76	72.7
	(P2) 120	19.8	15.8	76	73.8
	(P3)180	20.1	15.8	76	73.15
	Untreated	19.5	15.8	76	73.8

Frozen berry surface layer sections were observed under SEM before and after osmotic dehydration. Figure 5.2 shows a section of the fruit with waxy skin layer and a spot on the fruit where the surface layer is peeled off exposing the epithelial cell. Black color seen inside the cells was mainly water and other cellular constituents. These spots were more than at least five on a single whole berry. The damage of the fruit might have occurred during the freezing process or after freezing during storage. After freezing when packed in polythene bags, berries stick to each other, which might have left scars during their separation while thawing. From observation under SEM after osmotic dehydration, Figure 5.3 and Figure 5.4 showed white spots within the cell and were assumed as sugar crystals / molecules.

Preliminary Experiment with Blueberries: In summer 2005, a series of microwave drying experiments were conducted with fresh blueberries available in the market as a comparative study for saskatoon berries. Blueberries have similar physical and chemical properties to that of saskatoon berries. Even at low power microwave heating, the berries tend to burst open due to the enormous heating capability of the microwaves from material core. Results from the study are presented in Appendix B1. This study suggests that frozen berries physical state favors osmotic dehydration and drying but fresh berries should have a pre-treatment step before dehydration.

5.1.1. Effect on Osmotic Dehydration

Solute uptake was assessed by measuring the brix values after each stage of osmotic dehydration (Table 5.1), shows that pre-treatment had very minimal or no significant effect in increasing the osmotic reaction for both sucrose and high fructose corn syrup. One of the reasons for this could be immediate freezing of the fruit after harvest, which can disturb the integrity of berry structure. This can be seen in Figure 5.2, when a whole berry is observed under Scanning Electron Microscope (SEM), the epithelial layer with wax coated is disturbed and the epithelial cells are being exposed. These spots were more than one on a single fruit, which might as well help during osmotic dehydration process for the two-way diffusion process.

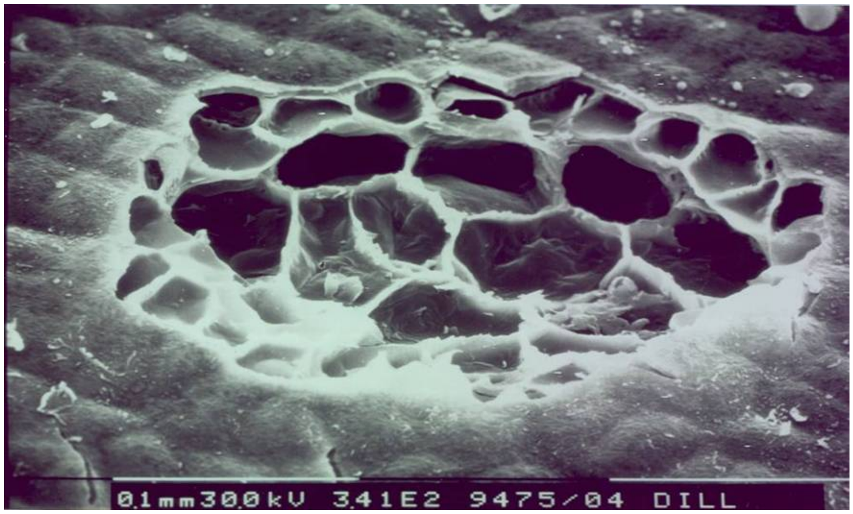

Figure 5.2 Frozen berry cut section of the berry skin under SEM

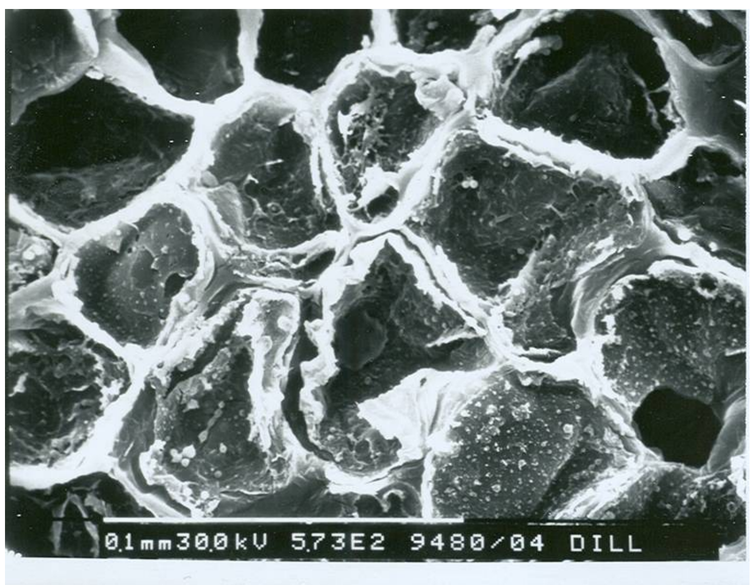

Figure 5.3 SEM of saskatoon berry osmotically dehydrated with 50% high fructose corn syrup (HFCS) solution for 24 h without chemical pre-treatment

Figure 5.4 SEM of saskatoon berry osmotically dehydrated with 50% sucrose solution for 24 h without chemical pre-treatment

5.2. Osmotic Dehydration (OD) Experiments

The effects of osmosis as a pre-treatment, mainly related to the improvement of nutritional, sensorial and functional properties of the products are analyzed. The distinctive aspect of this process when compared to other dehydration methods is the ‘direct formulation’ achievable through the selective incorporation of solutes without modifying the food integrity. By balancing the two main osmotic effects, water loss and soluble solids uptake, the functional properties of saskatoon berries could be adapted to many different food systems, functional foods and products development. For simplification, only two counter-diffusions are usually assumed to take place in osmotic dehydration process, with one being the water diffusing out from the inner cell to the surrounding solution and the other being the solute diffusing from the surrounding solution into the cell. Moisture Loss (ML, %) and Solute Gain (SG, brix or TSS) are the main parameters considered in this process.

5.2.1. Effect on Moisture Loss and Solid Gain

Table 5.2 Solid gain and Moisture loss during osmotic dehydration from 6 to 36 h duration

	Solute Gain (SG, brix)				Moisture Loss (ML, %)			
Sucrose	**6h**	**12h**	**18h**	**24h**	**6h**	**12h**	**18h**	**24h**
40	19.5	21.1	22.1	23.0	75.3	73.7	73.3	71.4
50	21.0	23.1	26.0	26.7	75.0	71.6	70.3	68.0
60	23.7	28.4	27.6	30.5	74.4	69.0	67.1	63.1
HFCS	**6h**	**12h**	**18h**	**24h**	**6h**	**12h**	**18h**	**24h**
40	22.3	24.8	25.0	27.2	74.1	72.1	71.1	68.5
50	23.8	28.4	28.9	32.1	71.4	69.8	66.7	64.9
60	24.7	30.4	31.9	34.8	70.6	66.8	63.7	60.6

Figure 5.5 and Figure 5.6 shows the evolution of water content from saskatoon berries during osmotic dehydration process using different concentrations of sucrose and high fructose corn syrup solutions. It can be seen that solute gain increases along with the increasing osmotic solution concentration in the range of 40-60% (Figures 5.7 and 5.8). Rate of ML and SG in sucrose solution during the initial phase (6 h period) was very slow for all concentrations and then highest rate of two-way diffusion was observed in the second phase (12 h period) of the osmotic dehydration process. After the second phase osmotic dehydration process follows a straight-line trend till the end of 24 h period. The diffusion rate after 24 h reduces very much and there is very less solute uptake during the next 12 h period. Table 5.2 shows the mean values of ML and SG for the 36 h osmotic dehydration process and both the factors had significant difference ($P<0.05$) with time, sugar solution concentration and interaction effect of time and solution concentration.

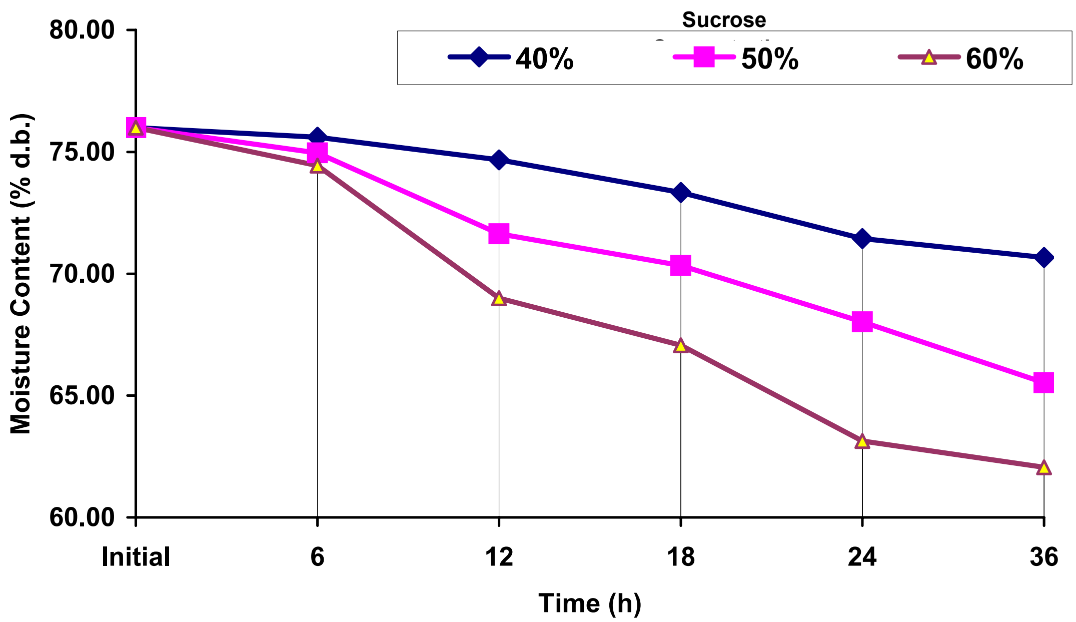

Figure 5.5 Moisture loss during the 36 h osmotic dehydration in sucrose solution at 40, 50 and 60% concentrations

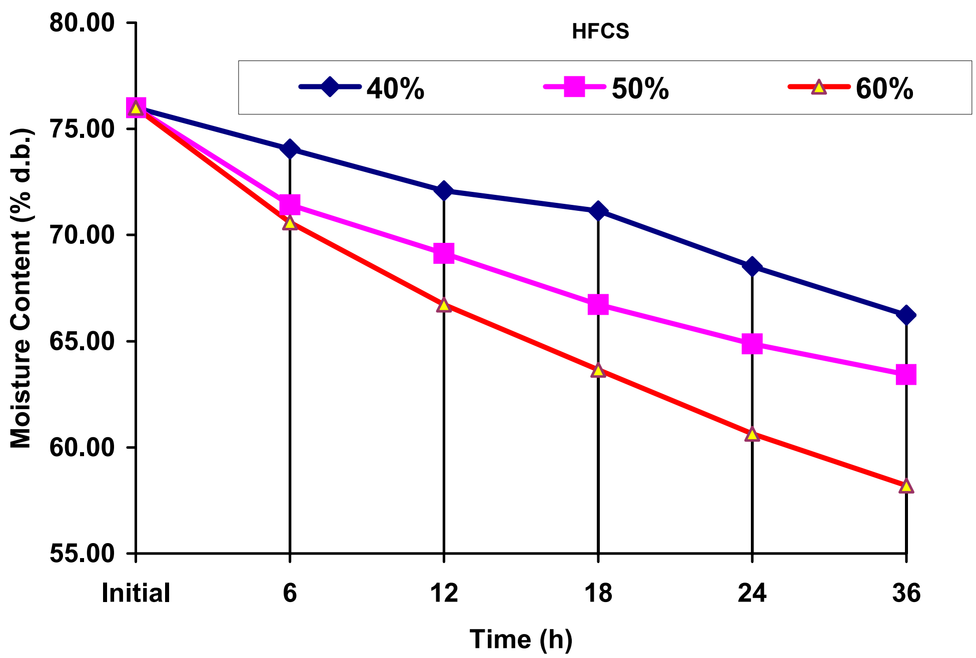

Figure 5.6 Moisture loss during 36 h osmotic dehydration in high fructose corn syrup (HFCS) solution at 40, 50 and 60% concentrations

5.2.2. Effect on Solute Gain

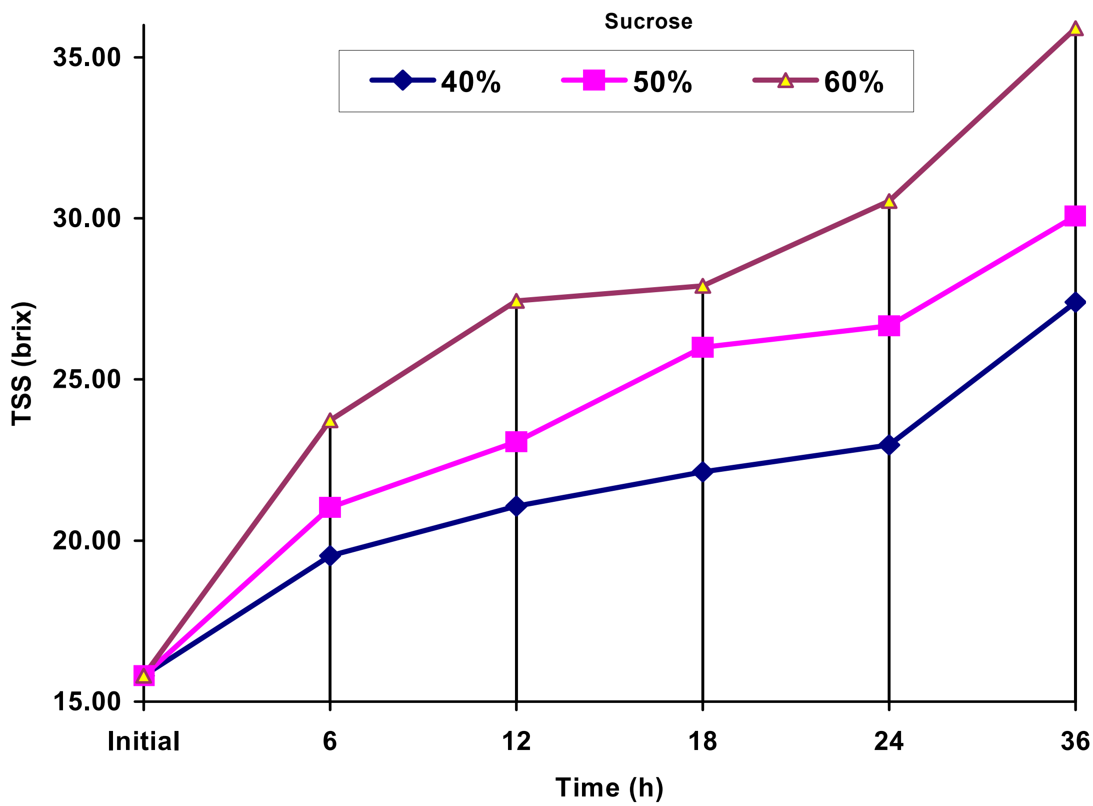

Figure 5.7 Solute gain during 36 h osmotic dehydration in sucrose solution at 40, 50 and 60% concentrations

The kind of sugar utilized as osmotic substance strongly affects the kinetics of water removal and the solid gain. By increasing the molar mass of solutes (HFCS), a decrease of solute gain and an increase of moisture loss were obtained, thus favoring weight loss and the dehydration aspect of the entire process. Glucose that has low molecular weight has a more profound effect on water activity depression than polysaccharides like sucrose (Argaiz et al., 1994). Therefore, when compared to sucrose medium, high fructose corn syrup revealed an effective water removal rate.

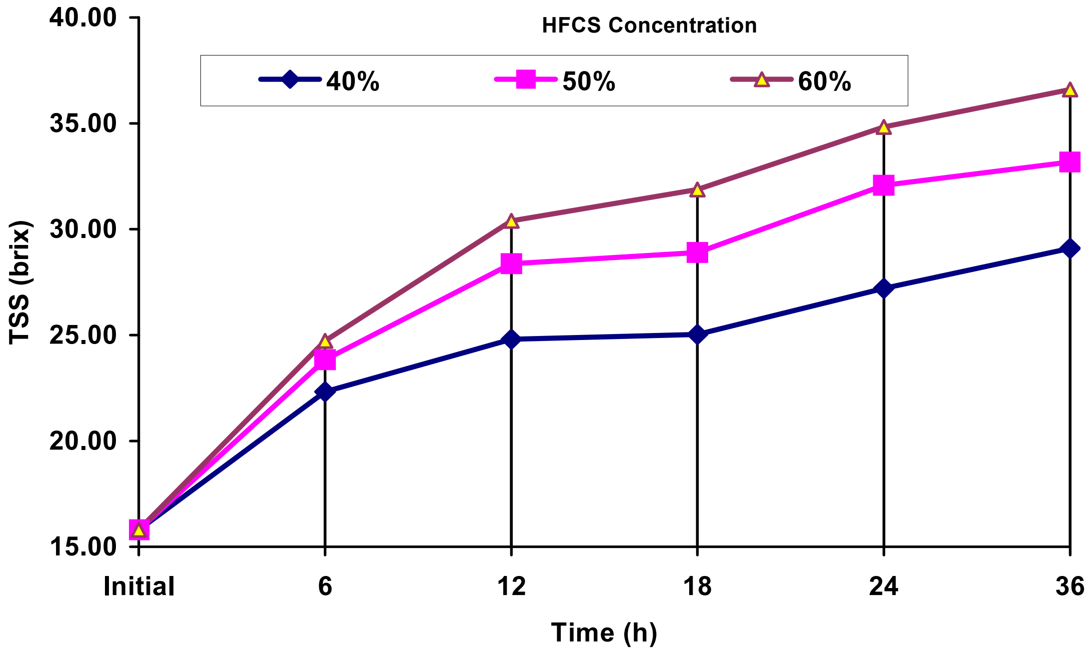

Figure 5.8 Solute gain during 36 h osmotic dehydration in high fructose corn syrup solution at 40, 50 and 60% concentrations

As osmotic dehydration is effective at ambient temperature, heat damage to color and flavor is minimized and the high concentration of the sugar surrounding fruit material prevents discoloration. In fruits, the cell wall membranes are living biological units, which can stretch and expand under the influence of growth and turgor pressure generated inside the cells. In natural food systems there is also some leakage of solute (sugars, organic acids, minerals, salts, etc.) across membrane. Though quantitatively negligible, it may be essential as far as organoleptic or nutritional qualities are concerned. Therefore, compared to single drying process, osmotic dehydration achieves a twofold transformation of the food item, by both a decrease in water content and a solute incorporation, which may result in a subsequent weight reduction.

5.2.3. Effect on Dielectric Properties

Loss of moisture can reduce the dielectric constant value and also solute gain with increase in dielectric loss factor values that affect the microwave absorption in microwave environments. So measurement of dielectric properties prior to microwave drying yielded useful information on energy absorption and dissipation levels for berries.

5.2.3.1. Effect on Dielectric Constant

The dielectric constant decreased with increasing solute concentration in the berry. The lower the moisture content, the lower the dielectric constant (Figure 5.9 and Figure 5.10).

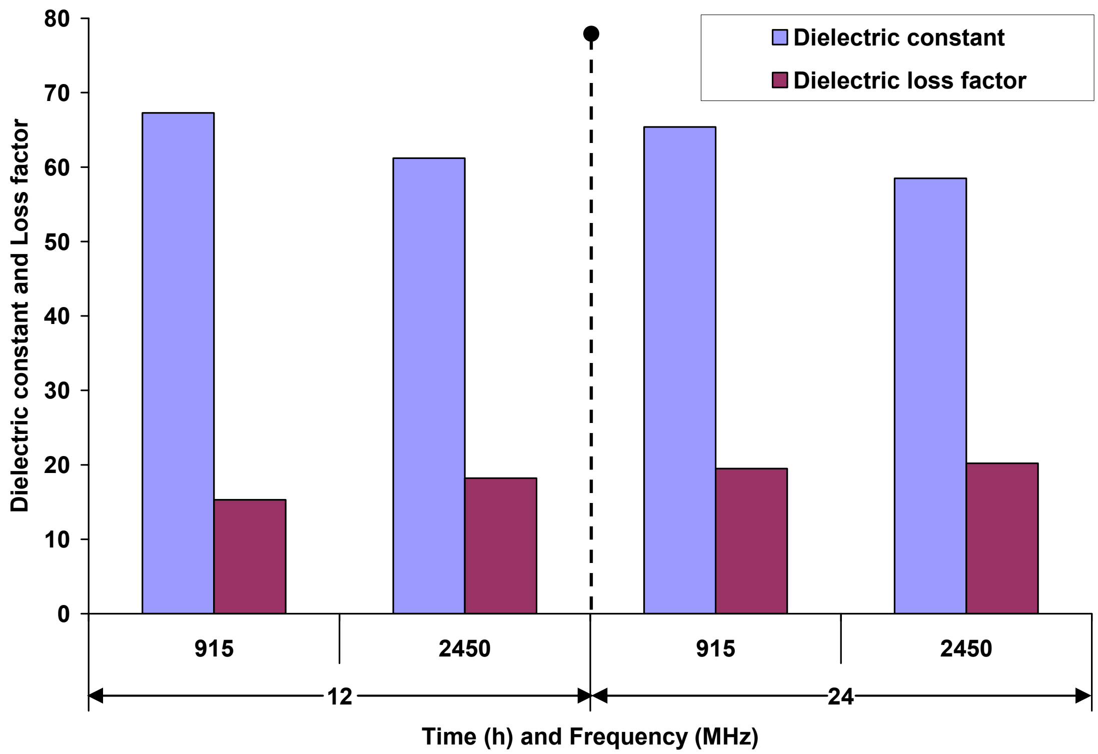

Figure 5.9 Osmotic dehydration effects on dielectric properties after 12 and 24 h durations at 50% high fructose corn syrup Concentration

This was expected, since water being a strong polar solvent in most foods, the molecules reoriented in response to changes in field polarity. Therefore, water component of the food contributed to the dielectric constant response. As discussed in Chapter 2.3.2.2 the higher the ash content (mostly composed of solutes), the lower will be the dielectric constant. Solutes bind with water molecules and decrease their ability to reorient themselves in response to the changing electromagnetic field direction and this lowers the dielectric constant.

5.2.3.2. Effect on Dielectric Loss Factor

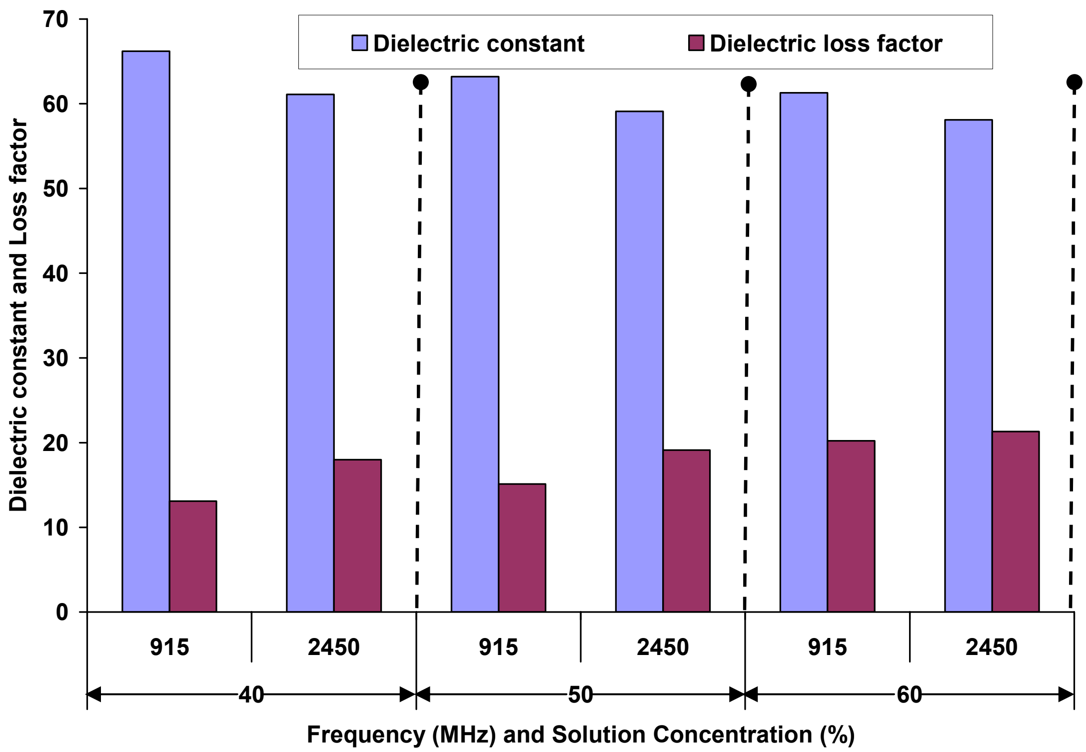

Figure 5.10 Osmotic dehydration effects on dielectric properties at 40, 50 and 60% high fructose corn syrup concentrations and respective frequencies (915 and 2450 MHz)

The moisture content-dielectric loss factor relationship reported in the literature is complex. Funebo and Ohlsson (1999) indicated that dielectric loss factor peaked at moisture content between 44 and 67% at 2800 MHz. Dielectric loss factor of maple syrup also decreases with increasing moisture content (35 to 98%) at 240 MHz. From Figures 5.9 and 5.10, it can be observed that increasing solute concentration and decreasing moisture content in the berry, resulted in an increase in dielectric loss factor values. For the two-step drying approach, further reduction of moisture was achieved under microwave conditions, as the sugar infused berry favors improved distribution of microwaves within the material and reduced drying time and energy.

5.3. Drying Characteristics

Drying of osmotic dehydration pre-treated and untreated saskatoon berries were done under:

- Microwave-only,
- Convection-only and
- Microwave-convection combination conditions.

The dryer system described in Chapter IV was used for microwave and combination drying whereas Thin-layer cross flow dryer discussed in Chapter 2.3.2.1 was used for convection drying studies. Drying is a crucial step in preservation of saskatoon berries, in bringing the M.C. from 75% (60% after osmotic dehydration) to 25% (or lower) in a very short time after harvest. Combined microwave-hot-air-drying was more effective in reducing the moisture content of saskatoon berries without damaging the quality attributes of the finished product. No similar work has been reported on saskatoon berry drying. The development of combined microwave-hot-air-drying system to produce high quality dried saskatoons in relatively short time could make significant contribution to the saskatoon berry industry.

Sugar infused into saskatoon berries during osmotic pre-treatment reduced drying rates during the second drying period as compared to untreated berries, and also osmotic dehydration reduced the total energy consumption on top of the preferential sensory characteristics of the final product. One energy-efficient drying technology was osmotic dehydration in combination with the above-mentioned drying operations. Such a hybrid technology was particularly advantageous when drying berries because a significant fraction of moisture was removed non-thermally with simultaneous infusion of desirable solutes. On the other hand, thermal drying after osmotic dehydration was necessary to reduce moisture content to its final value.

5.3.1. Drying Time

Drying rate is defined as the amount of water removed and time is shown in Figures 5.11 and 5.12 for berry samples during different drying conditions at 60, 70 and 80^{o}C. It is apparent that drying rate decreases continuously with improving drying time. The results indicated that diffusion was the most likely physical mechanism governing moisture movement in the berry samples. The results were generally in agreement with some literature studies on drying of various food products. Microwave drying alone without hot air conditions has higher drying rates and lower drying time than convection-only drying but combination drying is far more efficient. The drying time in microwaves can be reduced by 1.15 times at 60^{o}C and 2.36 times at 70^{o}C drying temperature when compared to convection drying.

Drying time varied from 26 to 200 min (Table 5.3) for the range of experimental parameters. The drying time in general decreased with the increase in microwave power level and further reduced the drying time during combination drying. The decrease being more with the increase in power level, in comparison to the increase in temperature indicating that the effect of microwave power level was more significant than temperature in reducing the drying time.

Table 5.3 Drying time and drying rate for untreated saskatoon berries

Microwave	Mean Drying Time (min)	Drying Rate (% MC/min)
Product temperature of 60^{o}C	165.67	0.31
Product temperature of 70^{o}C	58.33	0.87
Product temperature of 80^{o}C	44.33	1.15
Combination		
Product temperature of 60^{o}C	116.67	0.44
Product temperature of 70^{o}C	52.00	0.98
Product temperature of 80^{o}C	40.00	1.28
Convection		
Product temperature of 60^{o}C	192.33	0.27
Product temperature of 70^{o}C	138.33	0.37

5.3.1.1. Effect of Product-drying-temperature

Convection drying time of untreated berries at 60^{o}C product temperature was 192 min to dry the berries from 76% to 25% moisture content and at product temperature of 70^{o}C drying time reduced to 138 min, whereas microwave-combination drying the drying time was reduced by 1.64 and 2.65 times required for convection at the same product temperatures respectively. This can be attributed to the heating effect of microwaves to accelerate the diffusion of moisture from the center of the product to the periphery and with hot-air conditions around moisture removal from the periphery will also be enhanced. These results explain that the hot air heats the berry surface and minimize the heat loss from the berry volumetrically heated by microwave energy. Therefore the majority of the heat generated in berry by microwave energy could be used to heat and evaporate the water in berry efficiently.

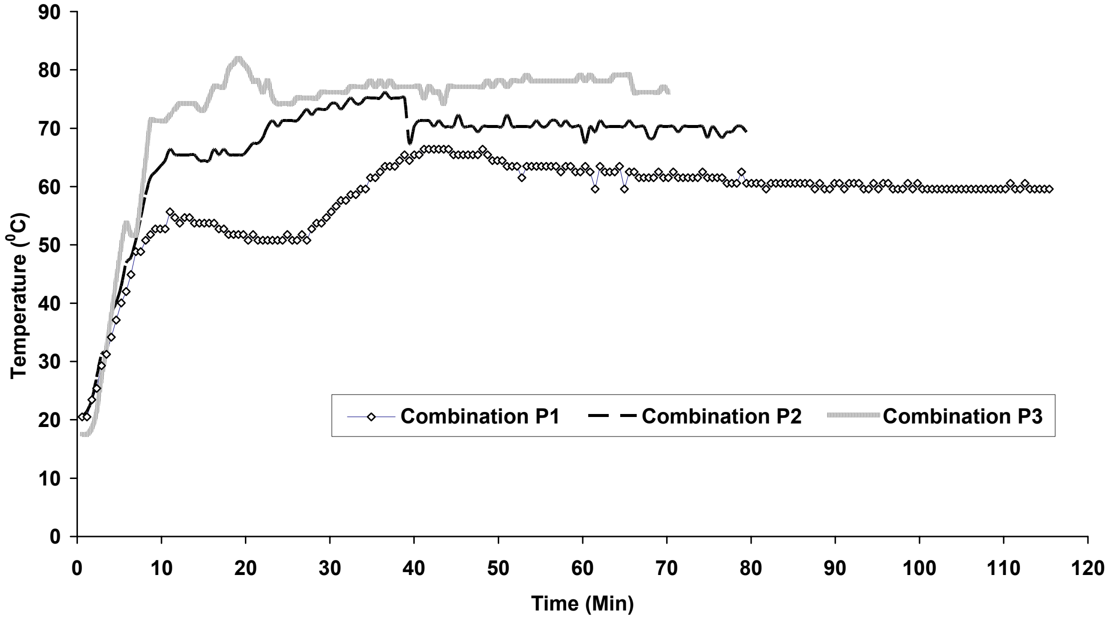

Figure 5.11 Drying temperature trends at combination P1, P2 and P3 levels (60, 70 and 80^{o}C respectively) and its effect on drying time

As shown in Figure 5.11, in combination drying of untreated berries the drying time reduced as the product drying temperature increased. The temperature trend in Figure 5.11 and Figure 5.12 shows that, the temperature rises in the first few minutes and then it tends to stabilize after the moisture content of the produce reduced. In the initial stages of drying, the moisture content is very high due to which higher microwave absorption was expected and observed. During combination drying, because of the higher drying rates the temperature stabilizes faster than in microwave drying.

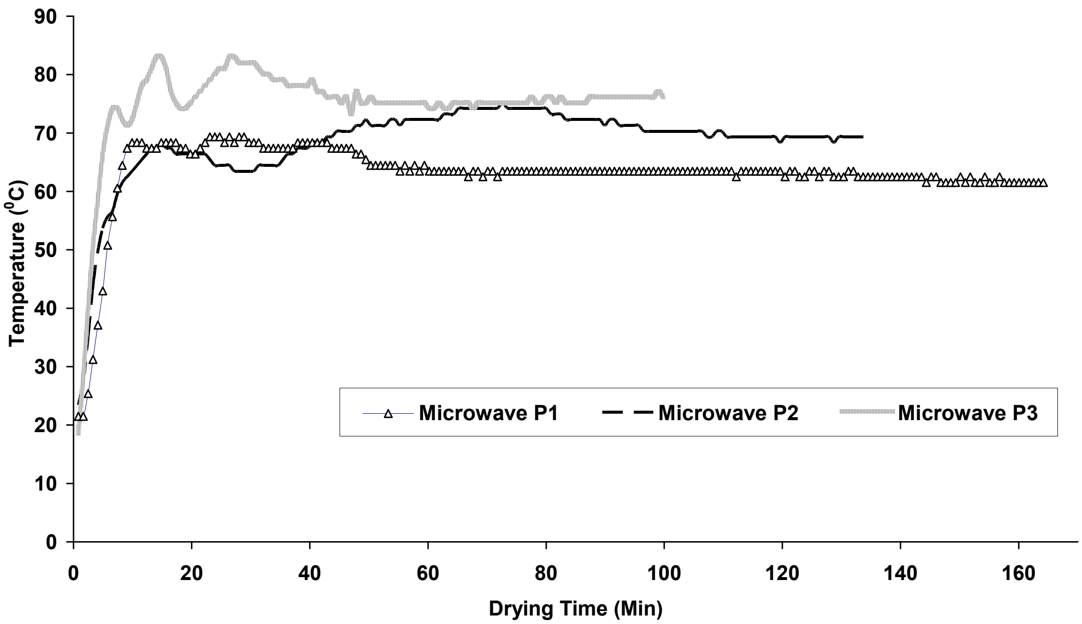

Figure 5.12 Drying temperature trends at microwave P1, P2 and P3 power levels (60, 70 and 80°C respectively) and its effect on drying time

5.3.2. Effect of Drying Mode

The drying time was reduced by nearly 45% with the combination mode compared to hot air drying, for untreated and treated berries. Microwave drying also reduced the drying time considerably over hot air drying in both the cases. The moisture content in the sample at different intervals was plotted against time (Figure 5.13 and Figure 5.14) as moisture curves for treated and untreated respectively. The curves indicate the higher drying rate with microwave-only and combination mode over hot air drying at any given time. The hot air drying method had a short constant rate period followed by a falling rate period. This was also reflected in the slight case hardening of the product. Microwave and combination drying had only a falling rate period in both cases. Combination mode had a higher falling rate indicating a higher rate of mass transfer, which resulted in a shorter drying time over hot-air and microwave drying. In general, the time required to reduce the moisture content to any given value was dependent on the drying conditions, being highest at microwave P1 (60^{o}C) and lowest at combination P3 (80^{o}C).

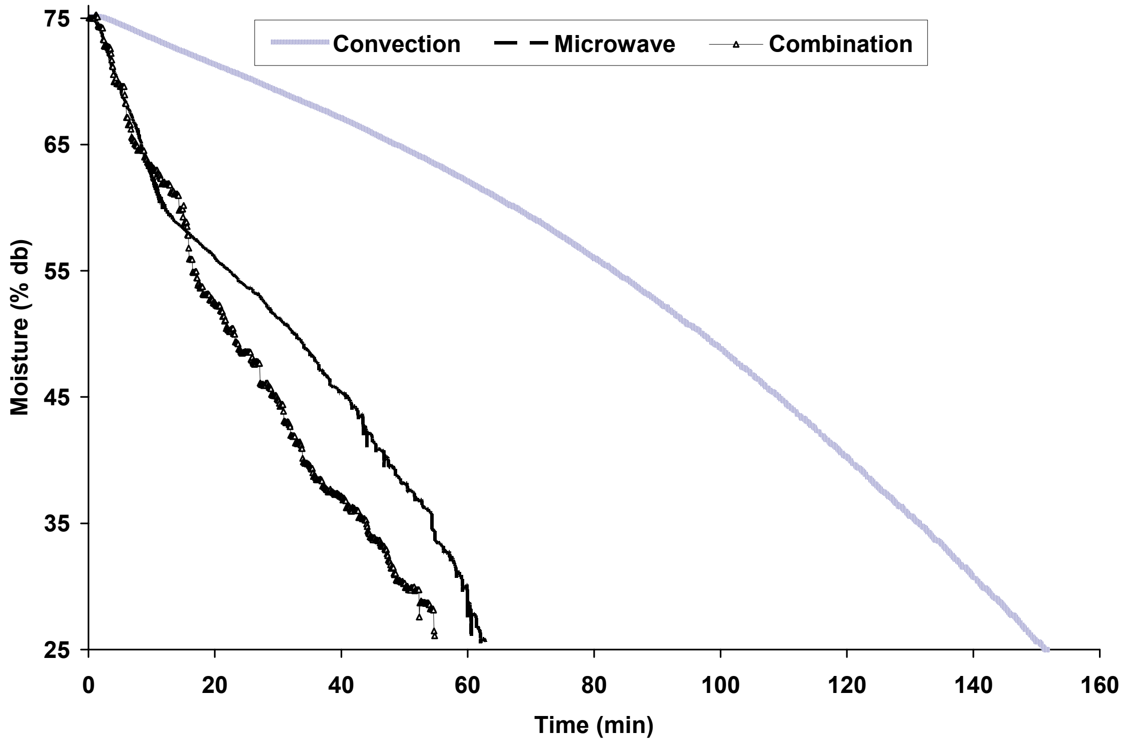

Figure 5.13 Drying of untreated berries at 70^{o}C under Microwave, Convection and Combination drying conditions

The drying rates were higher in the beginning of the drying process and gradually reduced as the drying process progressed. This was because of more radiation absorbed in the center and driving out moisture faster than the diffusion rate from the outer surface, causing moisture buildup towards the product surface after a few min. The drying rates increased with increase in microwave power, other conditions remaining the same and thus reducing the drying time.

5.3.3. Effect of Osmotic Dehydration on Drying

Osmotic dehydration as a pre-treatment for drying reduces moisture content by up to 17% which reduces the total drying time, as shown in Table 5.4, to dry the berries to 25% final moisture content.

Table 5.4 Drying time and drying rate for osmotic dehydration of saskatoon berries with sucrose (60% and 24h)

Microwave	Mean Drying Time (min)	Drying Rate (% MC/min)
Product temperature of 60^oC	117	0.44
Product temperature of 70^oC	52	0.99
Product temperature of 80^oC	33	1.55
Combination		
Product temperature of 60^oC	78	0.66
Product temperature of 70^oC	37	1.38
Product temperature of 80^oC	28	1.84
Convection		
Product temperature of 60^oC	132	0.39
Product temperature of 70^oC	88	0.58

The effect of sucrose and high fructose corn syrup dipping on the drying curves of saskatoons at 70^oC under microwave conditions is shown in Figure 5.14. The average moisture content (db) is plotted versus time, t (min) for Untreated and treated samples. No constant drying period was observed at any of the conditions studies. It can be observed that treatment with sucrose or high fructose corn syrup removed up to 10 or 19% of the initial moisture content for saskatoons that were soaked in 40, 50 and 60% brix solutions respectively. There is a reduction of drying time for treated berries by 15-20% of that required for microwave drying of untreated berries. This can be attributed to solvent distribution within the material to cause uniform heating and also the osmotic dehydration itself will reduce the moisture content of the initial sample.

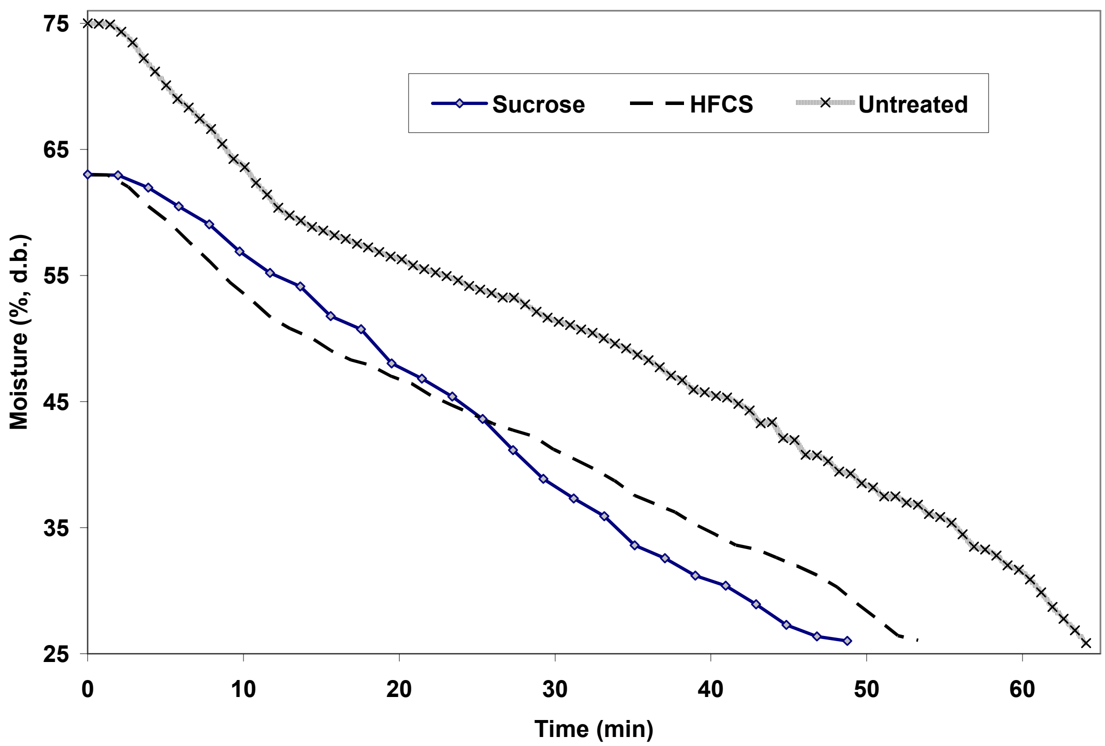

Figure 5.14 Microwave drying of osmotically treated and untreated berries at 70^{o}C

Secondary motivations for applying combined osmotic and microwave dehydration as a pre-treatment were:

- Possibility to produce unique (new) products with better taste,
- Improved flavor characteristics and/or increased nutritional value,
- Prevention of oxidation of the product and color stabilization,
- Improvement of the texture of the product such as higher final bulk volume of the product compared to heated air dehydration or microwave dehydration without osmotic pre-treatment,
- Due to shrinkage and weight loss after drying, storage and transport costs are reduced drastically, and
- Dried saskatoon berries after osmotic dehydration have various industrial applications such as bakery foods, nutraceutical industry etc.

5.4. Modeling of Drying Process

Many researchers have adopted due to the consideration of simplicity and accuracy, empirical models for drying data. The simple type of drying model assumes that rate of exchange in moisture content is proportional to the difference between moisture content and Equilibrium Moisture Content (EMC) of the material. The moisture content data at different microwave, combination and Convection temperature (power levels) were fitted against drying time, using the various models discussed in Chapter IV.

5.4.1. Evaluation of Thin-layer Drying Equation

Most of the researchers cited in the previous section adopted the fit standard error and the co-efficient of determination, R^2 as the criteria to evaluate the goodness of fit of drying equation. Recently residual plots have been adopted to evaluate more thoroughly the adequateness of the drying models. If the model can explain the observed values, the residuals would distribute randomly due to possible measuring errors. If the fixed error exists in the predicted model, the residual plots will indicate a significant pattern.

5.4.2. Data Analysis

Five thin-layer drying models were selected to evaluate the best fitting of the drying data. R^2 and Standard Error values for these equations are presented in Table 5.5 and from these Midilli equation gave best curve fit (R^2=0.99) for all convection (Figure 5.18) and microwave combination drying results whereas modified page equation gave consistent fit (R^2=0.98) for microwave drying results as shown in Figure 5.17. For some results obtained during combination drying also fitted with a good R^2 value in Sharma equation as shown in Figure 5.19. In general combination-drying data can fit in modified page equation, Sharma equation and Midilli equation with good R^2 value as shown in Figure 5.15, Figure 5.16 and Figure 5.19.

Table 5.5 Co-efficient of determination and standard error values for different equations

	Modified Page Equation		Sharma's Equation		Midilli Equation	
	R2	**Std. Error**	**R2**	**Std. Error**	**R2**	**Std. Error**
Microwave _P2	0.988	1.159	-	-	-	-
Microwave_P1 (Sucrose OD)	0.9851	1.219	-	-	-	-
Microwave_P2 (Sucrose OD)	0.97	2.04	-	-	-	-
Microwave_P3 (Sucrose OD)	0.976	1.398	-	-	-	-
Combination_P1 (Sucrose OD)	-	-	0.997	0.503	0.9996	0.1875
Combination_P2 (Sucrose OD)	0.959	2.082	0.994	0.826	0.9933	0.842
Combination_P3 (Sucrose OD)	0.9708	1.675	0.9993	0.248	0.9999	0.129
Combination_P2	0.9893	1.041	-	-	0.987	1.253
Convection_P2	0.998	0.729	-	-	0.9769	2.222
Convection_P1 (Sucrose OD)	0.953	2.42	-	-	0.9986	0.421

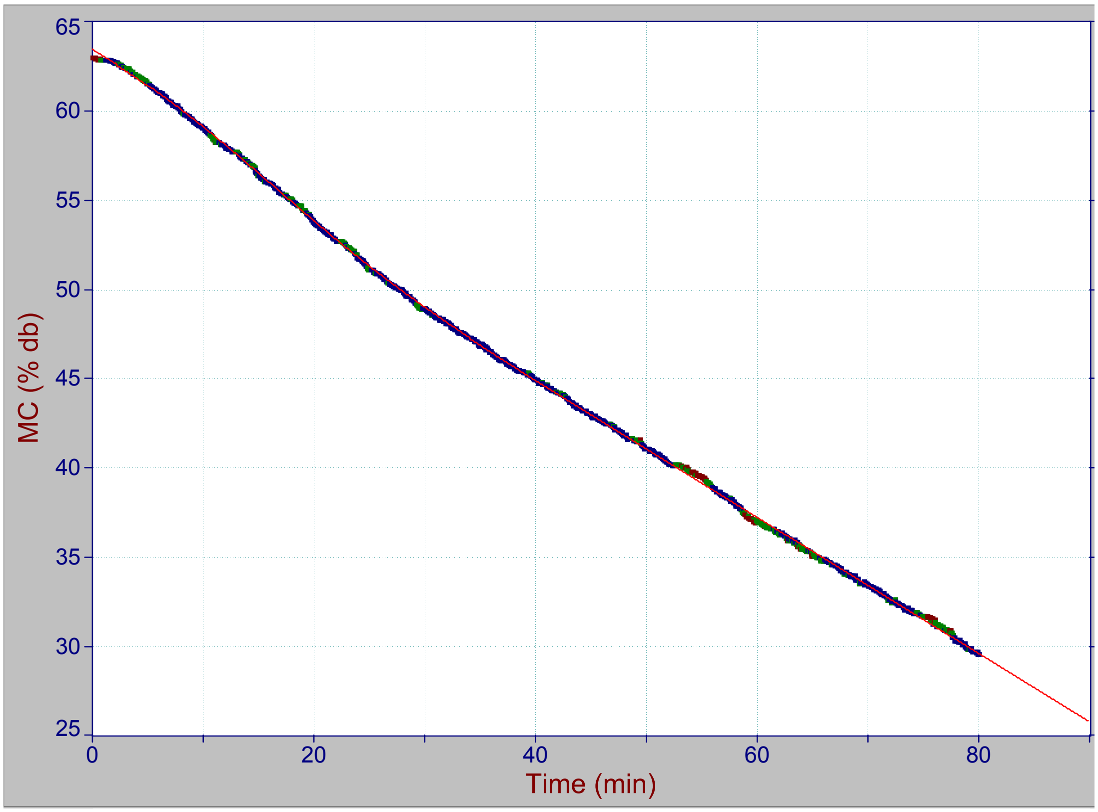

Figure 5.15 Midilli equation drying curve fit for sucrose osmotic dehydration combination drying at 60°C

For combination drying data of saskatoon berries after osmotic dehydration, Midilli equation fitted very well with R^2=0.999 Standard Error = 0.129.

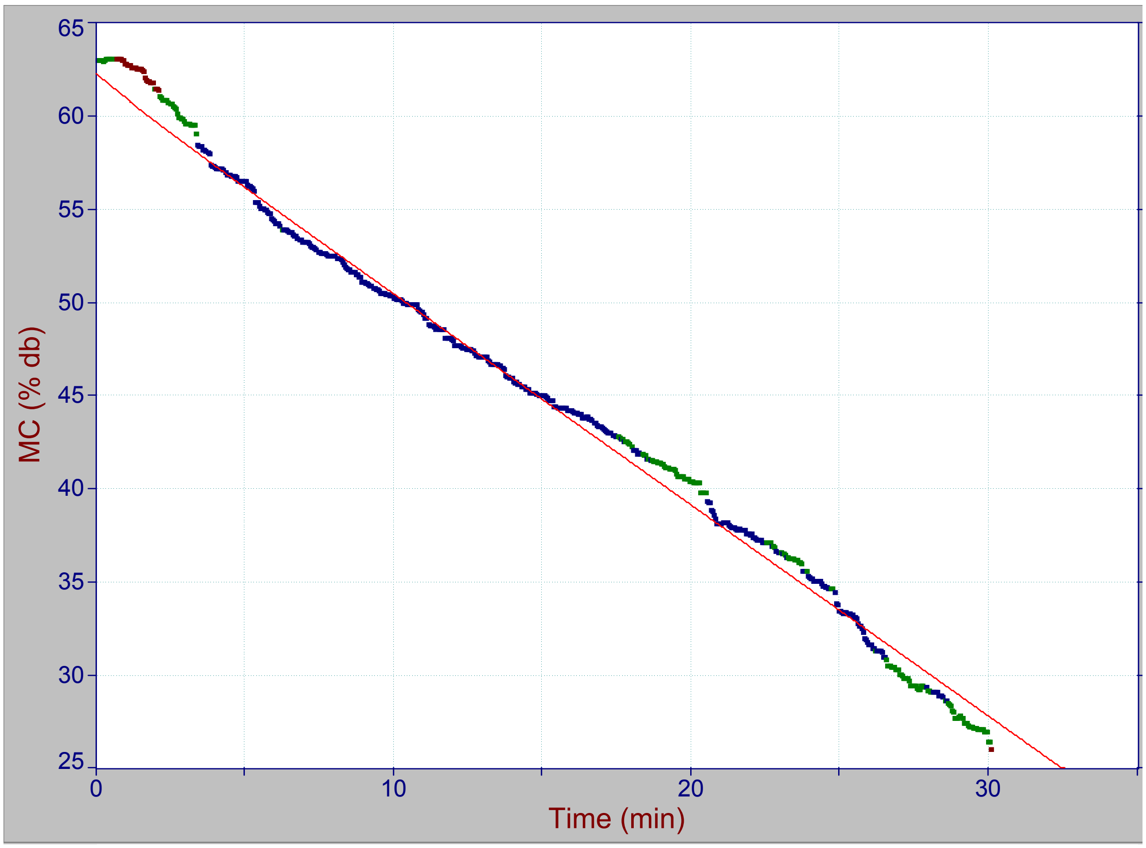

Figure 5. 16 Modified drying equation drying curve fit for sucrose combination drying at 80°C

For combination drying data of saskatoon berries after osmotic dehydration, Modified drying equation fitted with R^2=0.986 and Standard Error = 1.273.

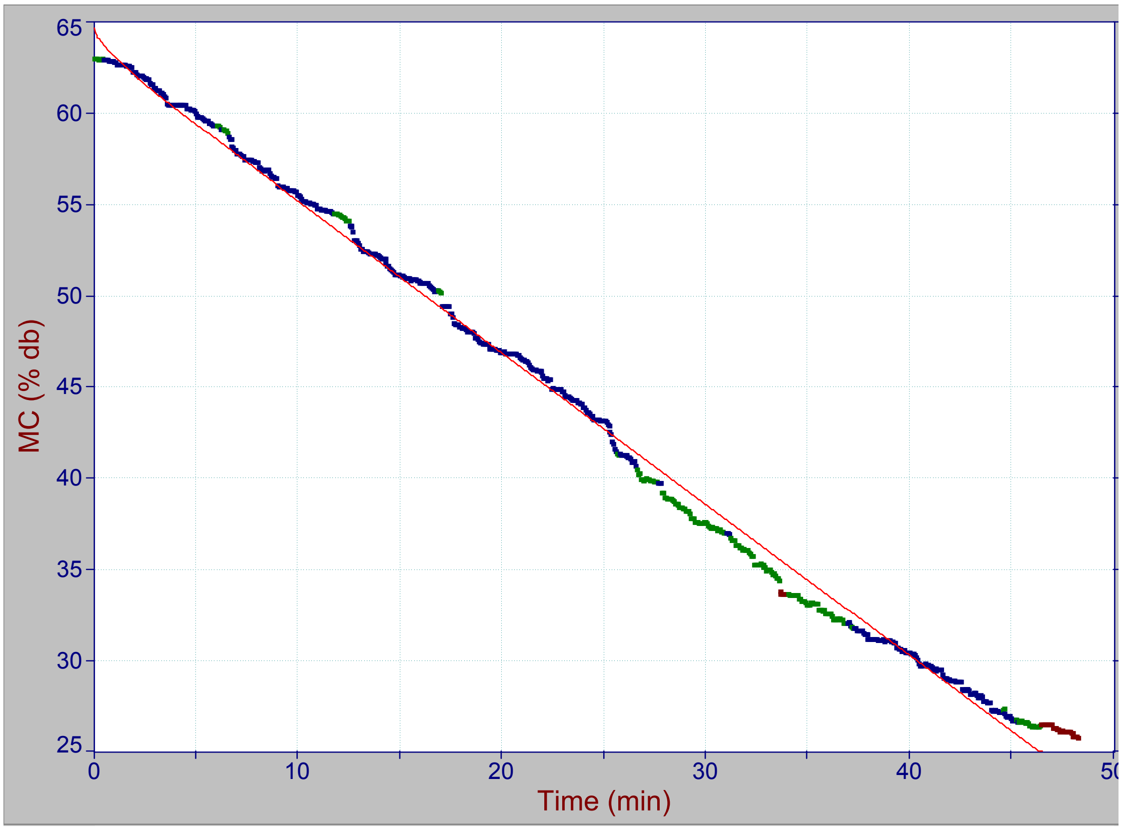

Figure 5.17 Midilli equation drying curve fit for sucrose osmotic dehydration microwave drying at 70°C

For microwave drying data of saskatoon berries after osmotic dehydration, Midilli drying equation fitted with R^2=0.995 and Standard Error = 0.788.

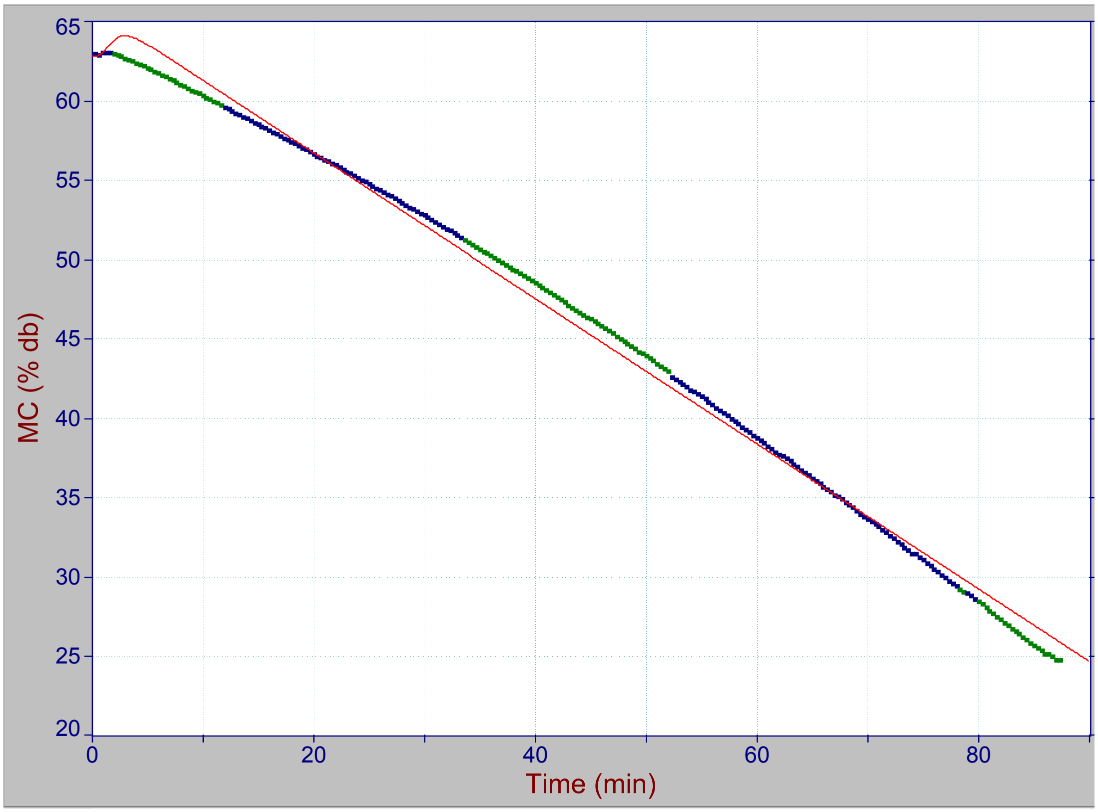

Figure 5.18 Midilli equation drying curve fit for sucrose osmotic dehydration convection drying at 70°C

For convection drying data of saskatoon berries after osmotic dehydration, Midilli drying equation fitted with R^2=0.995 and Standard Error = 0.782.

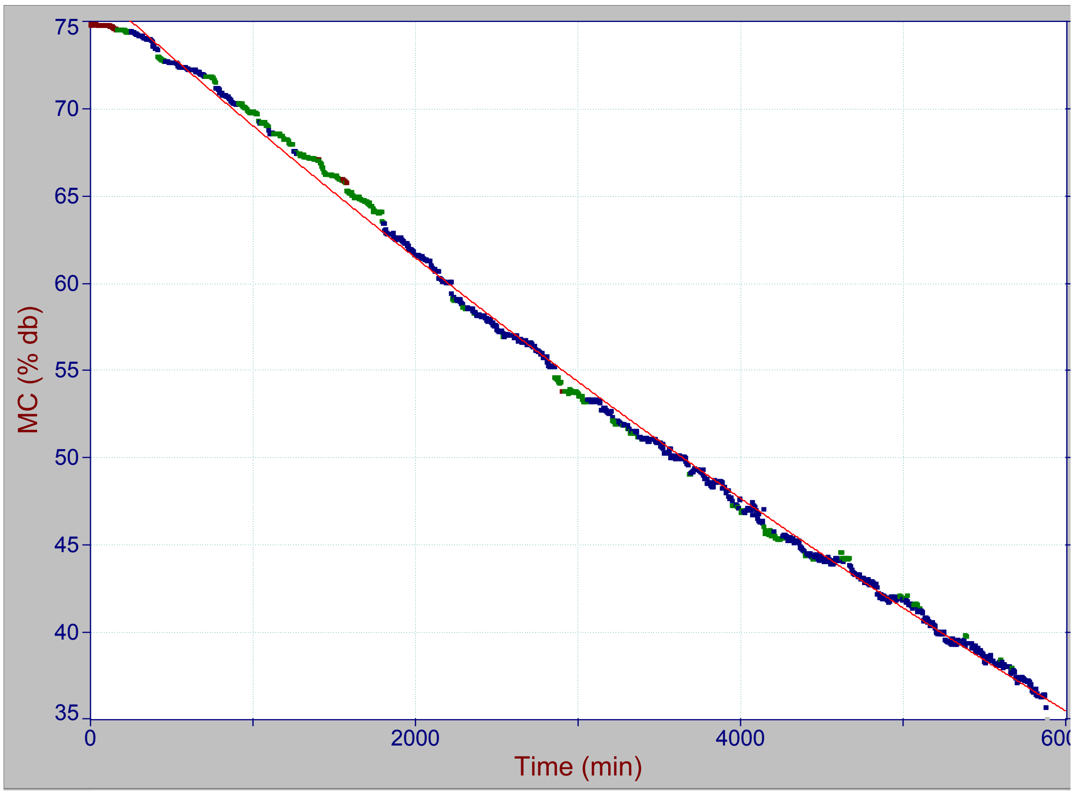

Figure 5.19 Sharma's equation drying model curve fit for combination drying method at 60°C

For combination drying data of saskatoon berries, Sharma equation fitted with R^2=0.998 and Standard Error = 0.579.

5.4.3. Quality Analysis

Dehydrated saskatoon berries were analyzed for the quality changes that might have occurred due to all the different treatments. Rehydration ratio and color changes were the two main quality parameters considered.

5.4.3.1 Rehydration Ratio

Changes in the original dimensions and shape occur simultaneously and water diffusion affects the rate of the moisture loss during drying. Researchers have pointed out that the volume change process is one of the main sources of error for drying simulation models of biological products. There is significant volume shrinkage during the drying process of high moisture content products such as vegetables (Hatamipour and Mowla, 2002).

Table 5.6 Rehydration ratio of Microwave dried berries with and without osmotic dehydration

	Treatments	Rehydration Ratio
1	**Untreated**	
	At product temperature of 60^{o}C	0.24
	At product temperature of 70^{o}C	0.22
	At product temperature of 80^{o}C	0.21
2	**Osmotic dehydration with Sucrose**	
	At product temperature of 60^{o}C	0.42
	At product temperature of 70^{o}C	0.40
	At product temperature of 80^{o}C	0.39
3	**Osmotic dehydration with HFCS**	
	At product temperature of 60^{o}C	0.47
	At product temperature of 70^{o}C	0.47
	At product temperature of 80^{o}C	0.46

Untreated saskatoon berries dried under microwave at 60^{o}C had a rehydration ratio 0.24 that reduced with increasing the product temperature to 70^{o}C and 80^{o}C and a highest of 0.24 rehydration ratio was during microwave drying at product temperature of 60^{o}C as shown in Table 5.6. In general, the rehydration ratio decreased with increase in product temperatures during drying. As Potter and

Hotchkiss (1995) reported, increasing temperature cause distortion of cells and capillaries in plant tissue, which may lead to textural changes, thus lowing water absorption and adsorption characteristics affecting rehydration ability and rehydration ratio. osmotic dehydration with sucrose and high fructose corn syrup increases the rehydration ratio by around twice that of untreated berries. High fructose corn syrup osmotic dehydration berries after drying had significantly ($P<0.05$) higher rehydration ratio when compared to sucrose. Drying method did not have a significant difference in changing the rehydration ratio (Table 5.7).

Table 5.7 Rehydration ratios of sucrose osmotic dehydrated berries at different drying conditions

	Treatments	Rehydration Ratio
1	**Microwave dried**	
	At product temperature of 60^{o}C	0.42
	At product temperature of 70^{o}C	0.40
	At product temperature of 80^{o}C	0.39
2	**Combination dried**	
	At product temperature of 60^{o}C	0.43
	At product temperature of 70^{o}C	0.40
	At product temperature of 80^{o}C	0.40
3	**Convection dried**	
	At product temperature of 60^{o}C	0.43
	At product temperature of 70^{o}C	0.43
	At product temperature of 80^{o}C	0.42

5.4.3.2 Color Analysis

Hunter lab colorimeter values of dried saskatoon berries are shown in Table 5.8. The Hunter ‘L’ measures lightness and varies from 100 for perfect white to zero for black, approximately as the eye would evaluate it. Hunter ‘a’ measures yellowness when positive and greenness when negative and ‘b’ measures yellowness when positive and blueness when negative. The hunter 'L, 'a', 'b' values for saskatoon berries decreased with the increase in drying temperature during all drying modes. The total color difference was minimal for convection, but for microwave and combination drying the values were around 4 to 5.

Table 5.8 Hunterlab colorimeter parameters of untreated and sucrose pretreated berries under microwave, convection and combination drying conditions

Sample	ΔL	Δa	Δb	ΔEab
Untreated				
Microwave P1	-0.96	-1.41	0.67	1.83
Convection P2	-1.21	-1.38	0.01	1.84
Convection P3	-2.46	-2.23	-0.84	3.42
Sucrose Pretreated				
Microwave P2	-1.92	-2.00	-0.65	2.85
Microwave P3	-3.86	-3.29	-1.72	5.36
Convection P1	-0.62	-2.20	-0.46	2.34
Convection P2	-2.52	-1.56	-0.88	3.09
Combination P2	-2.29	-2.37	-0.83	3.40
Combination_P3	-3.32	2.79	0.11	4.34

Table 5.9 revealed that greatest color difference with all treatments was obtained at the highest power level. The greater heating should have lead to faster darkening, with some possibility of occurrence of imperceptible burnt spots. Microwave dried berries at 60^{o}C product temperature gave least total color difference of 1.83.

5.5 Summary of Chapter V

The laboratory scale microwave combination dryer was successfully developed for drying of saskatoon berries under both microwave and microwave combination conditions. Microwave combination drying resulted in lowered drying time and also with increase in microwave power levels, drying time was reduced significantly. Osmotic dehydration as a pretreatment to drying reduced up to 15% moisture from the berries and also introduced solutes.

CHAPTER VI - CONCLUSIONS

6.1 Conclusions

Production of saskatoon berries as a commercial crop has gained importance in North America and is being exported to other countries for consumption and processing because of its nutraceutical value and consumer acceptance. This also calls for new post harvest techniques for shelf life extension and processing in the manufacture of new saskatoon berry products. Freezing is the only post harvest technique reported till date to preserve the berries for year-long consumption. So microwave and microwave combination drying technique study after osmotic dehydration was explored in this study as a post harvest preservation technique for saskatoon berries.

i. The microwave-convection combination dryer system was developed and successfully tested. The obtained temperature and moisture loss recorded was accurate enough with minimal errors.
ii. The developed drying system with the modified settings can be used for drying / dehydration studies of other agricultural / food materials (e.g. blueberries, beef etc.).
iii. The data obtained from drying of untreated and treated saskatoon berries showed that microwave and microwave combination drying proves to be a faster way of bringing moisture content to safer levels and also preserve the product quality.
iv. The reported drying characteristics of saskatoon berries dried under microwave, microwave-convection conditions were reasonable and were in closer proximity to the reported literature.
v. Microwave drying of saskatoon berries at product temperatures of 60^{o}C and 70^{o}C after osmotic dehydration retained their quality attributes in the same range, but drying time required at 70^{o}C product temperature was reduced to half.

vi. Osmotic dehydration of saskatoon berries with high fructose corn syrup sugar solution had 3% less moisture after 24 h period compared to sucrose sugar solution treatment and this difference was significant.

vii. Drying after osmotic dehydration reduced the drying time in all drying conditions studied because of the structural changes that may have occurred at the surface (semi-permeable membrane) giving rise to higher diffusion rates.

viii. Microwave drying had relatively higher drying rates than convection and this was due to the higher dielectric loss factor value in osmotic dehydrated berries that favor microwave absorption.

ix. Microwave combination drying was efficient with time and energy consumption by upto 20% than microwave-only.

x. LabView programs were developed for real-time temperature and weight-loss measurement and acquisition.

6.2. Recommendations for Future Work

i. Drying studies with fresh saskatoon berries during the harvesting season can add more value to this research in developing a new post harvest technique for saskatoon berries,
ii. Drying characteristics study at very low microwave power levels and to compare the quality characteristics of the final product is suggested,
iii. Control of microwave power to the lowest possible wattage with a variable rheostat and solid-state relay circuit and the temperature data can be acquired from Fiso signal conditioner. Installation of a filament transformer to the magnetron circuit to keep the filament to continuously run is a prerequisite,
iv. Sample holder rotation system on the horizontal axis with 180^{o} turn on either side could improve the microwave distribution with in the material and more even drying of the berries, and
v. Modeling of drying data heat and mass transfer simulation using FEM-Lab or advanced simulation software is also suggested.

References

Achanta, S. and M. R. Okos. 1995. Predicting the quality of dehydrated foods and biopolymers- research needs and opportunities. *Drying Technology*. 14 (6): 1329-1368.

Adapa, P.K., S. Sokhansanj and G.J. Schoenau. 2002. Performance study of Re-circulation cabinet dryer using a household dehumidifier. *Drying Technology*. 22(8): 1673-1689.

Al-Mahasneh, M. A., S.J. Birrell, C.J. Bern and K. Adham. 2001. Measurement of corn mechanical damage using Dielectric properties. *Transactions of ASAE*, 2001 Annual International meeting. Paper Number: 10-1073.

Annon. 1991. From duff to puff. *Food Manufacture*. 10 : 47-48.

AOAC. 1990. *Official Methods of Analysis*, Association of Official Analytical Chemists, Inc, Virginia. 2: 69-81.

Argaiz, A., A. L. Malo, E. Palou and J. Welti. 1994. Osmotic dehydration of papaya with corn syrup solids. *Drying Technology*. 12(7): 1709-1725.

ASAE Standards. 1992. S352.2. Moisture measurement - Grain and Seed. *In ASAE Standards,* 39th edition.

ASAE Standards.1999. D293.2. Dielectric properties of grain and seed. *In ASAE Standards*, 2003.

Beaudry, C. 2001. Evaluation of drying methods on osmotically dehydrated cranberries. *Unpublished M.Sc. thesis*. Montreal, QC: Department of Agricultural and Biosystems Engineering, McGill University.

Bouraout, M., P. Richard and T. Durance. 1994. Microwave and convective drying of potato slices. *Journal of Food Process Engineering*, 17, 353-363.

Buffler, C. R. 1993. *Microwave cooking and processing: Engineering fundamentals for the food scientist*. Van Nostrand Reinhold. New York.

Chuy, L. E., T. P. Labuza. 1994. Caking and stickiness of dairy-based food powders as related to glass transition. *Journal of Food Science*. 55 : 1231-1239.

Contreras, J. E. and T. G. Smyrl. 1981. An evaluation of osmotic concentration of apple rings using corn syrup solid solutions. *Canadian Institute of Food Science and Technology*. 14 (310).

Dixon, G. M., J. J. Jen and V. A. Paynter. 1976. Tasty apple slices result from combined osmotic dehydration and vacuum-drying process. *Food Process Development*. 18 (113).

Engelder, D. S. and C. R. Buffler. 1991. Measuring dielectric properties of food products at microwave frequencies. *Microwave World.* 12(4): 6–15.

Erle, U., H. Schubert. 2000. Combined osmotic and microwave-vacuum dehydration of apples and strawberries. *Journal of Food Engineering*.49:193-199.

Feng, H. and J. Tang. 1998. Microwave finish drying of diced apples in a spouted bed. *Journal of Food Science*. 63: 679-683.

Feng, H, J. Tang, R.P. Cavalieri. 2001. Dielectric properties of dehydrated apples as affected by moisture and temperature. *Transactions of ASAE*, 45(1): 129-135

Funebo, T. And T. Ohlsson. 1998. Dielectric properties of some fruits and vegetables. *Journal of Microwave Power and Electromagnetic Energy*, submitted.

Funebo, T. and T. Ohlsson. 1999. Microwave-assisted air dehydration of apple and mushroom. *Journal of Food Engineering*, 38, 353-367.

Genin, N. and F. Rene. 1995. Analyze du role de la transition vitreuse dans les procedes de conservation agro-alimentaries. *Journal of Food Engineering*. 26 : 391-408.

Grabowski, S. and A.S. Mujumdar. 1992. Solar-assisted osmotic dehydration. pp. 367-404. *In: Drying of Solids*, A.S. Mujumdar (Ed.). International Science Publisher, NY.

Grabowski, S., A.S. Mujumdar, H.S. Ramaswamy, and C. Strumillo. 1994. Osmo-convective drying of grapes. *Drying Technology*. 12(5): 1211-1219.

Green, R.C. and G. Mazza. 1986. Relationships between anthocyanins, total phenolics, carbohydrates, acidity and color of saskatoon berries. *Canadian Institute of Food Science and Technology.* 19:107-113.

Harrington, W.O., C.H. Hills, S.B.Jones, A.E. Stafford and B.R. Tennes. 1978. Ethyl oleate sprays to reduce cracking of sweet cherries, *Horticultural Science*. 13: 279-280.

Hatamipour, M. S. and D. Mowla. 2002. Shrinkage of carrots during drying in an inert medium fluidized bed. *Journal of Food Engineering*. 55 (3) : 247-252.

Hawkes, J. and J. M. Flink. 1978. Osmotic concentration of fruit slices prior to freeze dehydration. *Journal of Food Processing and Preservation*. 2 (265).

Huxsoll, C. C. 1982. Reducing the refrigeration load by partial concentration of food prior to freezing. *Food Technology*. 5 (98-102).

Islam, M. N. and J. M. Flink. 1982. Dehydration of potato. II. Osmotic concentration and its effect on air drying behaviour. *Journal of Food Technology*. 17 (387).

Kostaropoulos, A.E. and G.D. Saravacos. 1995. Microwave pretreatment of sun-dried raisins. *Journal of Food Science*. 60: 344-347.

Khraisheh, M. A., T. J. R. Cooper, and T. R. A Magee. 1997. Microwave and air drying I. Fundemental considerations and assumptions for the simplified thermal calculations of volumetric power absorptions. *Journal of Food Engineering*. 33 (207-219).

Lenart, A. P. P. Lewicki. 1990. Osmotic dehydration of apples at high temperature. *In International Drying Symposium' 89* (A. S. Mujumdar and M. Roques, eds.(, Hemishpere Publishing Co., New York, 501.

Lewicki, P. and A. Lenart. 1990. Energy consumption during osmo-convection drying of fruits and vegetables. Pp. 354-366. *In: Drying of Solids*, A.S. Mujumdar (Ed.). International Science Publisher, NY.

Maskan, M. 2000. Microwave/air and microwave finish drying of banana. *Journal of Food Engineering*, 44, 71-78.

Masi, P. and M. Riva. 1988. Modeling grape drying kinetics. *Preconcentration and Drying of Food Materials*. 203-214.

Mazza, G. 1979. Development and consumer evaluation of a native fruit product. *Canadian Institute of Food Science and Technology*. 12(4):166-169.

Mudgett, R.E., E. C. To, D.I. Wang. 1974. Dielectric Properties of food materials. *Journal of Microwave Power.* 9: 303–315.

Mazza, G. 1982. Chemical composition of saskatoon berries (*Amelanchier alnifolia* Nutt.). *Journal of Food Science*. 47:1730-1731.

Mazza, G. and M.W. Hodgins. 1985. Benzaldehyde, a major aroma component of saskatoon berries. *Horticultural Science*. 20:742-744.

Mazza, G. 1986. Anthocyanins and other phenolic compounds of saskatoon berries (*Amelanchier alnifolia* Nutt.). *Journal of Food Science*. 51:1260-1264.

Mazza, G. and C.G. Davidson. 1993. *Saskatoon berry: A fruit crop for the prairies*. p. 516-519. In: J. Janick and J.E. Simon (eds.), New crops. Wiley, New York.

Mudgett R E. 1986. Electrical properties of foods. *In: Engineering Properties of foods* (Rao M.A. and S. S. H. Rizvi), Chapter 7. Marcel Dekker, Inc., New York, NY.

Mujumdar, A. S. 1995. (Ed.), Convective transport in infrared drying, *Drying'92* (pp. 695–703). The Netherlands: Elsevier

Mui, W., Durance, T.D. and Scaman, C.H. 2002. Comparison of headspace volatiles, sensory characteristics and texture of banana chips dried by combinations of hot-air, vacuum and microwaves. *Journal of Agricultural and Food Chemistry* 50(7): 1883-1889.

Nelson, S. O. 1973. Electrical properties of agricultural products - a critical review *Transactions of ASAE* 16 384–400

Nelson, S.O. 2001. Dielectric properties of food materials and electric field interactions. In: Ashim KD, Ramaswarmy C (eds). *Handbook of Microwave Technology for Food Applications*. New York: Marcel Dekker, New York. 69–107.

Panther, M. and F. H. Wolfe. 1972. Studies on the degradation of ascorbic acid by saskatoon berry juice. Journal *of Canadian Institute for Food Science and Technology*. 5 (2):93-96.

Ponting, J. D. and D. M. McBean. 1970. Temperature and dipping treatment effects on drying rates and drying times of grapes, prunes and other waxy fruits. *Food Technology*. 4 (633-649).

Potter, N.N., J.H. Hothchkiss. 1995. *Food Science*, 5th edition, Chapman and Hall, New York. 476.

Prabhanjan, D.G., H.S. Ramaswamy, G.S.V. Raghavan. 1995. Microwave assisted convective air drying of thin layer carrots. *Journal of Food Engineering*. 25: 283-293.

Raghavan, G.S.V., V. Orsat and M.S.Venkatesh. 2005. Microwave Processing of Foods. *Stewart Postharvest Review* 1(2:3):1-8.

Rahman, M.S. and J. Lamb. 1991. Air drying behaviour of fresh and osmotically dehydrated pineapple. *Journal of Food Engineering*. 14: 163-171.

Rahman, M.S., C.O. Perera. 1996. Effect of pre-treatment on air drying rates and thin layer drying kinetics of fresh cherry. *Drying 96.* Volume B: 1053-1060.

Ramaswamy, H.S. and F. Nsonzi. 1998. Convective air-drying kinetics of osmotically pre-treated blueberries. *Drying technology*, 16(3-5): 743-759.

Ranganna, S. 1986. *Hand Book of Analyses of Quality Control for Fruits and Vegetables,* Tata McGraw Hill Publishing Co. Ltd., New Delhi. 931-932.

Ratti, C., and Mujumdar, A. S. 1995. Infrared drying, (Ed.), *Handbook of industrial drying.* 567–588.

Reddy, L. N., V. Meda and M.D. Pickard. 2004. Combined convection, microwave and infrared processing of agricultural materials. Presented at *Annual ASAE meeting*, Aug 1-4, Montreal, QC, Canada.

Reddy, L. N., V. Meda and B. Shrestha. 2005. Dielectric properties of saskatoon berries (Amelanchiar alnifolia) at different pretreatment and osmotic conditions. *In Proceedings of CSAE/ASAE Intersectional meeting*. Sept 29-30, Winnipeg, MB, Canada.

Reddy, L. N. and V. Meda. 2005. Osmotic Dehydration and Combination Drying Technique for Prairie fruits. *In Proceedings of International Microwave Power Institute*, July 13-15, 2005, Seattle, WA, USA.

Risman, P.O. 1991. Terminology and notation of microwave power and electromagnetic energy. *Journal of microwave power and Electromagnetic energy*, 26, 243 – 250.

Sapers, G.M., S.B. Jones and J.G. Phillips. 1985. Leakage of anthocyanins from skin of thawed, frozen highbush blueberries (*Vaccinium corymbosum* L.). *Journal of Food Science.* 50: 432–436.

Sarosi, H. and A. Polak. 1976. Possibilities of application of osmotic drying in the food industry. *Tudomanyos Kozlemenyck, Elelmiszeripari Foiskala*. 6 (63).

Sharma, G. P., R. C. Verma and P. Pathare. 2005. Thin-layer infrared radiation drying of onion slices. *Journal of Food Engineering*, 67, 361-366.

Sheridan, P. and N. Shilton. 1999. Application of far infra-red radiation to cooking of meat products. *Journal of Food Engineering*. 41: 203-208.

Somogyi, L,P. and B.S. Luh. 1986. Dehydration of foodstuffs. *Commercial Fruit Processing* 353-405.

Somogyi, L.P, H.S. Ramaswamy and Y.H. Hui. 1996. *Processing Fruits: Science and Technology – Biology, principles and applications* 14-24.

Tulasidas, T.N., G.S.V. Raghavan and E.R. Norris. 1993. Microwave and convective drying of grapes. *Transactions of ASAE* 36(6): 1861-1865.

Turner, N.J., C. L.C. Thompson, M.T. Thompson and A.Z. York. 1990. *Thompson Ethnobotany*. Royal British Columbia Museum: Victoria. Pp 253-257.

Turner, N.J. 1997. *Food plants of Interior First peoples*. UBC Press: Vancouver. 139.

Venkatachalapathy, K and G.S.V. Raghavan. 1997. Osmotic and Microwave drying of blueberries. *Proceedings of the 32 Microwave Power Symposium*, Ottawa, Canada. International Microwave Power Institute, USA.

Venkatesh, M. S. 1996. M. Sc. Thesis: *Cavity perturbation technique for measurement of dielectric properties of some agri-food materials*. McGill University, Quebec, Canada.

Venkatesh, M. S., E. St-Denis, G. S. V. Raghavan, P. Alvo and C. Akyel 1998. Dielectric properties of whole, chopped and powdered grain at various bulk densities. *Journal of Canadian Agriculture Engineering.* 40 (3): 191-200.

Venkatesh, M.S. and Raghavan, G.S.V. 2005. An Overview of Dielectric Properties Measuring Techniques, *Canadian Biosystems Engineering*, 47, 715-730.

Westphal, W. B. and A. Sils. 1972. *Dielectric constant and loss data*. Report: Air Force Materials Laboratory, Air Force Command, Dayton, Ohio. 72-79.

Wolfe, F. H. and F. W. Wood. 1972. Non-volatile organic acid and sugar composition of saskatoon berries during ripening. *Journal of Canadian Institute for Food Science and Technology*. 4: 29-30.

Yang, C.S.T. and W.A. Atallah. 1985. Effect of four drying methods on the quality of intermediate moisture lowbush blueberries. *Journal of Food Science*. 50: 1233-1237.

Yang, A.P.P., C. Wills and C.S.T. Yang. 1987. Use of combination process of osmotic dehydration and freeze drying to produce a raisin type low bush blueberry product. *Journal of Food Science*. 52: 1651-1653.

Yongsawatdigul, J. and Gunasekaran, S. 1996. Microwave-vacuum drying of cranberries: Part II. Quality evaluation. *Journal of Food Processing and Preservation*, 20, 145-156.

http://www.agr.gov.sk.ca/docs/statistics/crops/horticulture/fruitveggies040226.pdf http://www.devonian.ualberta.ca/pwatch/saskat.htm

http://www.prairieplant.com/wp-s-chart.html

http://www.saskchamber.com/documents/259Action_Saskatchewan_Special_Feature_11.pdf

http://www.saskatoonberries.com

http://www.infrareadyproducts.com. Infraready Products Ltd., Saskatoon, Canada.

APPENDIX

This section includes all the additional data for drying, dielectric properties, preliminary studies, scanning electron microscope images and also digital images of microwave dryer system with individual instrumentation. Temperature trends explained in Section 5.3.2 are presented at other drying conditions.

Appendix A1. Microwave Combination Drying at 60, 70 and 80^{o}C

Drying data (weight loss, g) for untreated and osmotically dehydrated berries at different product drying temperatures (60, 70 and 80^{o}C) under microwave-convection combination conditions with respect to time are shown in this part of the appendix.

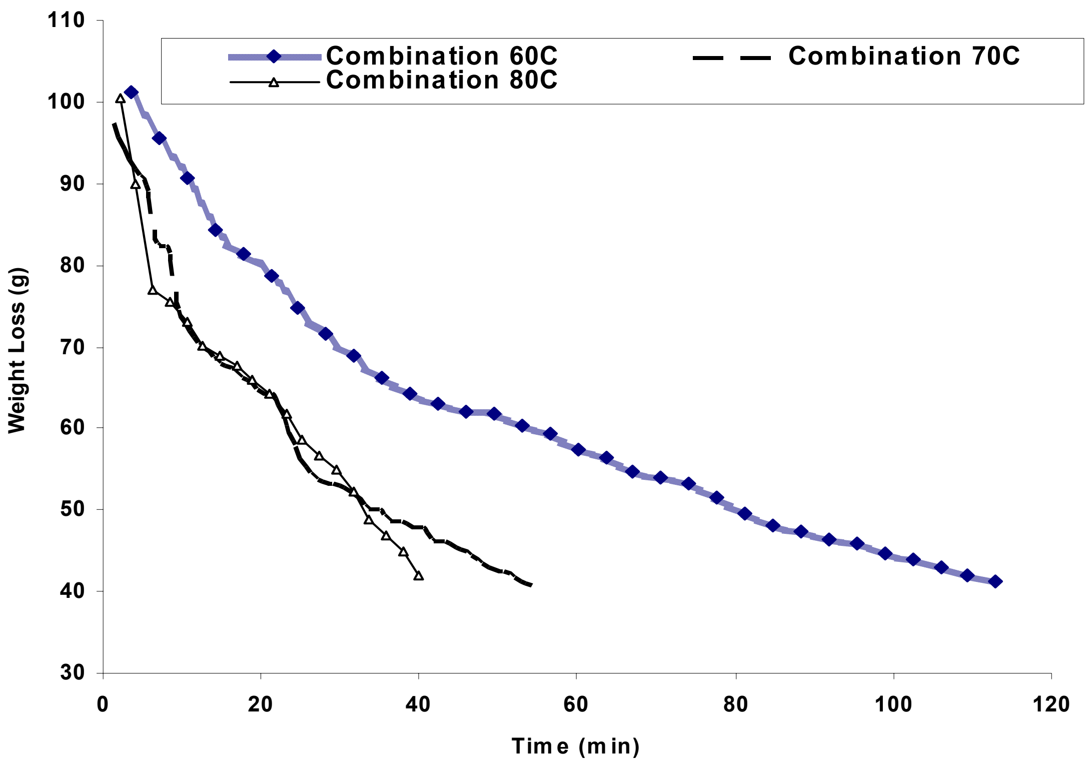

Figure A1 Microwave combination drying of untreated saskatoon berries at 60, 70 and 80^{0}C temperatures and corresponding weight loss plotted against time (min)

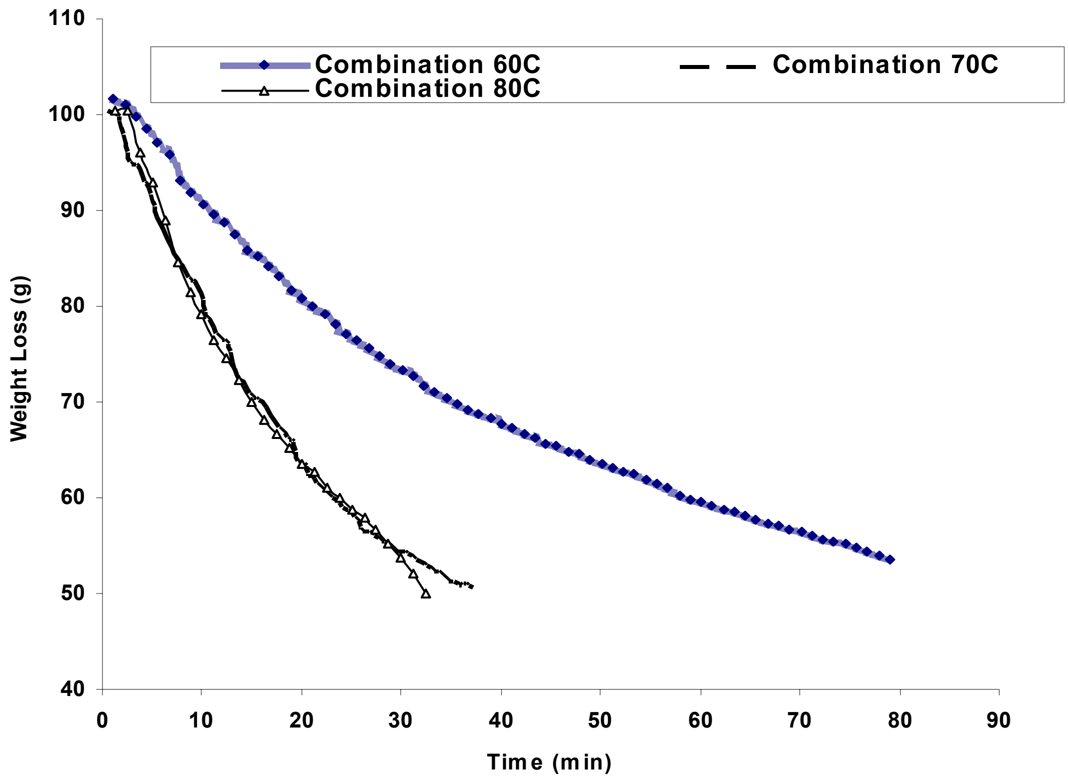

Figure A2 Microwave combination drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 60, 70 and 80^{0}C temperatures and corresponding weight loss plotted against time (min)

Appendix A2. Microwave drying at 60, 70 and 80^0C

Drying data (weight loss, g) for untreated and osmotically dehydrated berries at different product drying temperatures (60, 70 and 80^0C) under microwave conditions with respect to time are shown in this part of the appendix.

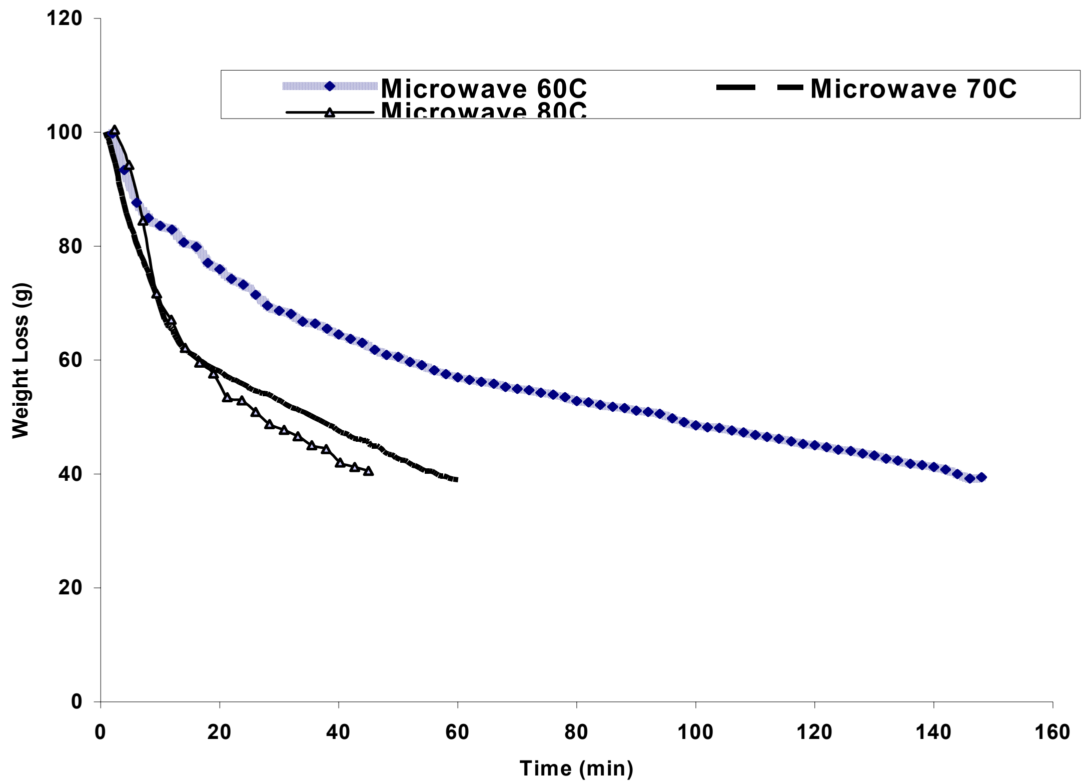

Figure A3 Microwave drying (weight loss, g) of untreated saskatoon berries at 60, 70 and 80^0C temperatures and corresponding moisture loss plotted against time (min)

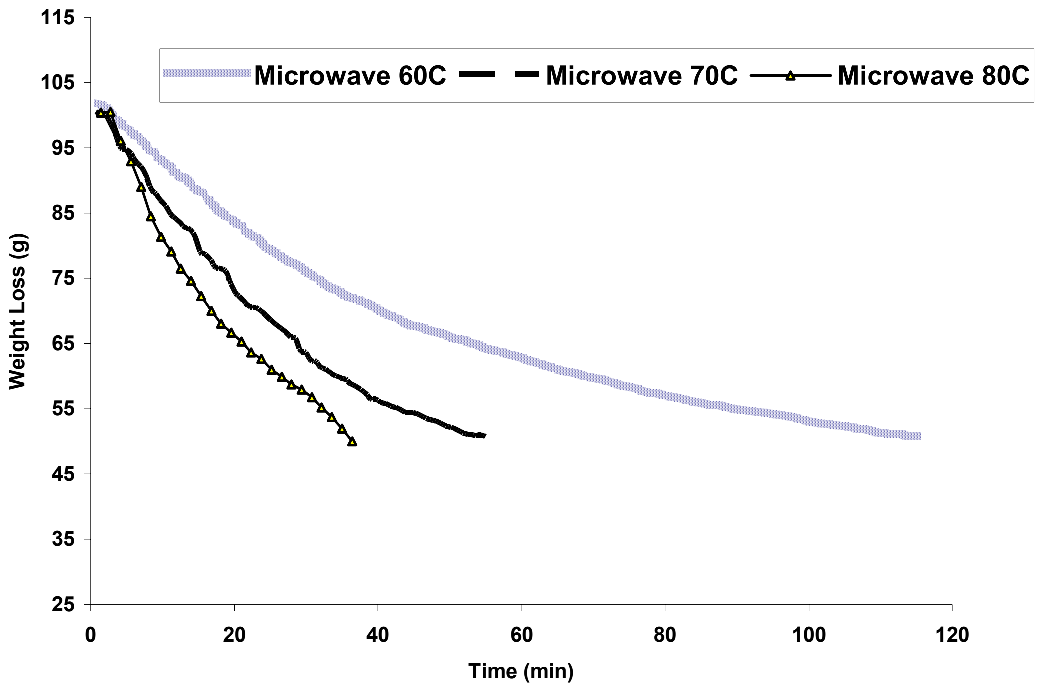

Figure A4 Microwave drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 60, 70 and 80^{0}C temperatures

Appendix A3. Convection drying at 60, 70 and 80^{0}C

Drying data (weight loss, g) for untreated and osmotically dehydrated berries at different product drying temperatures (60, 70 and 80^{0}C) under convection conditions with respect to time are shown in this part of the appendix.

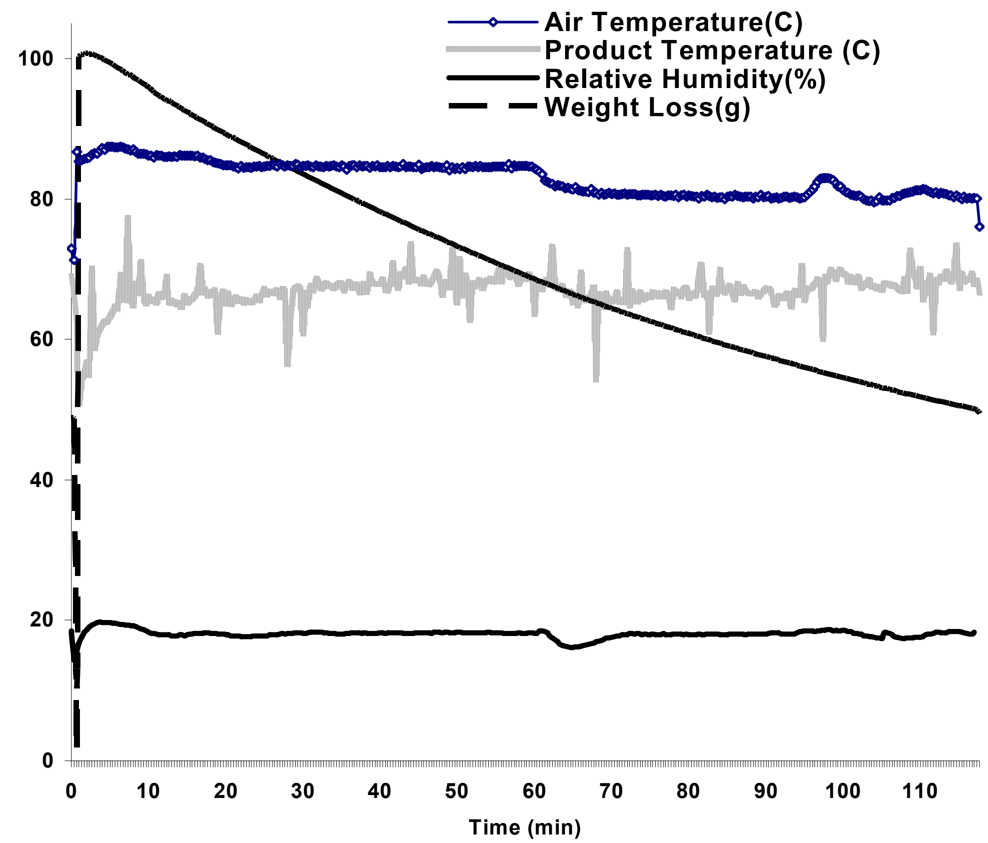

Figure A5 Convection drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 60^{0}C temperature

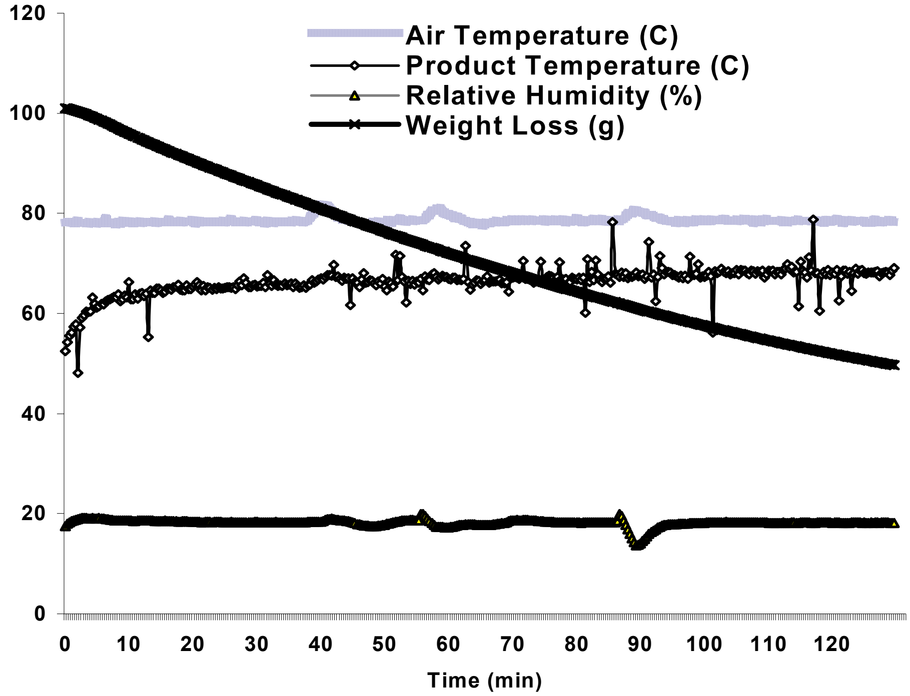

Figure A6 Convection drying (weight loss, g) of high fructose corn syrup osmotic dehydrated saskatoon berries at 60^0C temperature

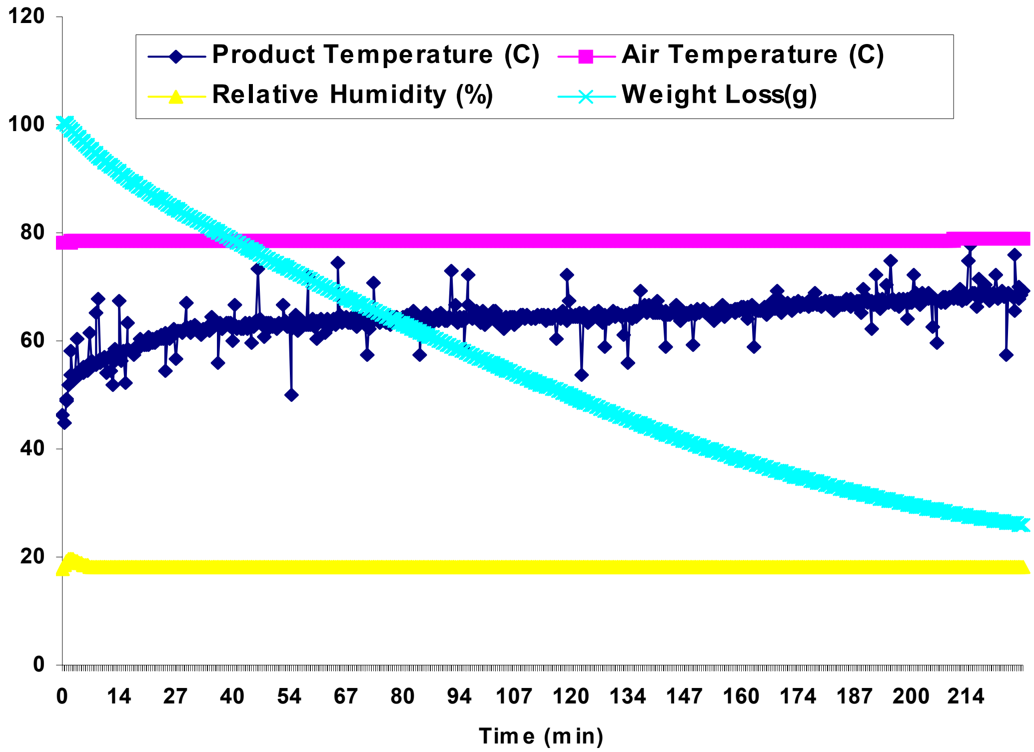

Figure A7 Convection drying (weight loss, g) of untreated saskatoon berries at 60^0C temperature

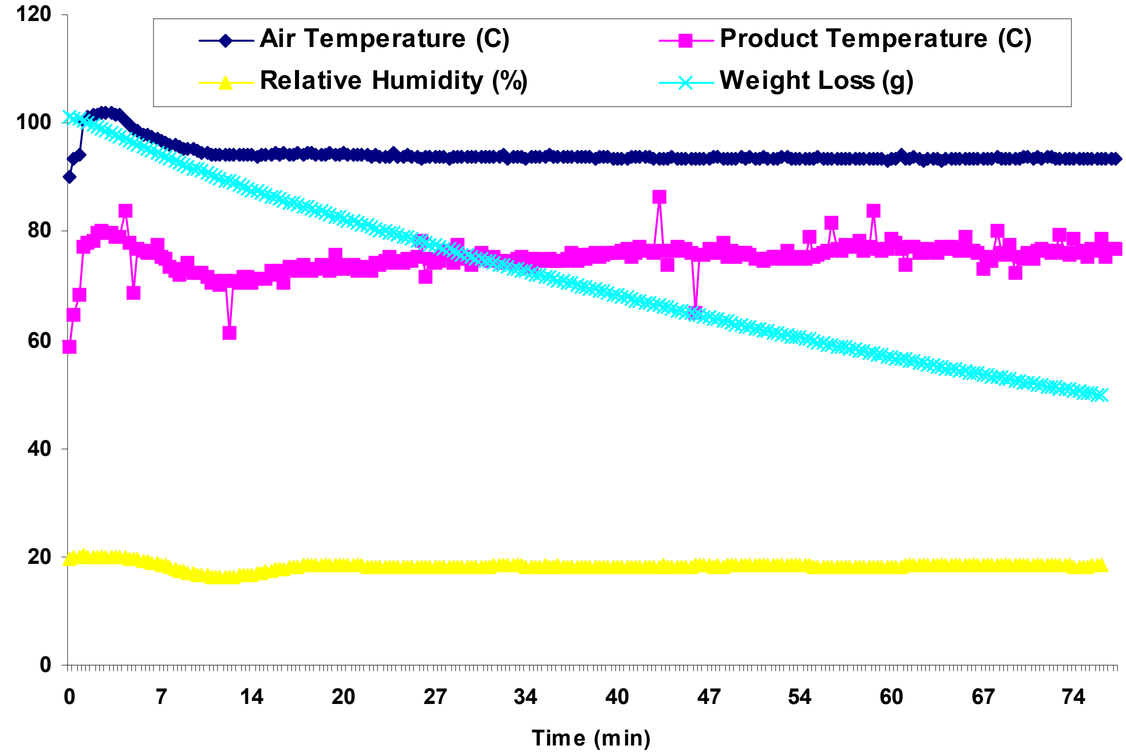

Figure A8 Convection drying (weight loss, g) of sucrose osmotic dehydrated saskatoon berries at 70^{0}C temperature

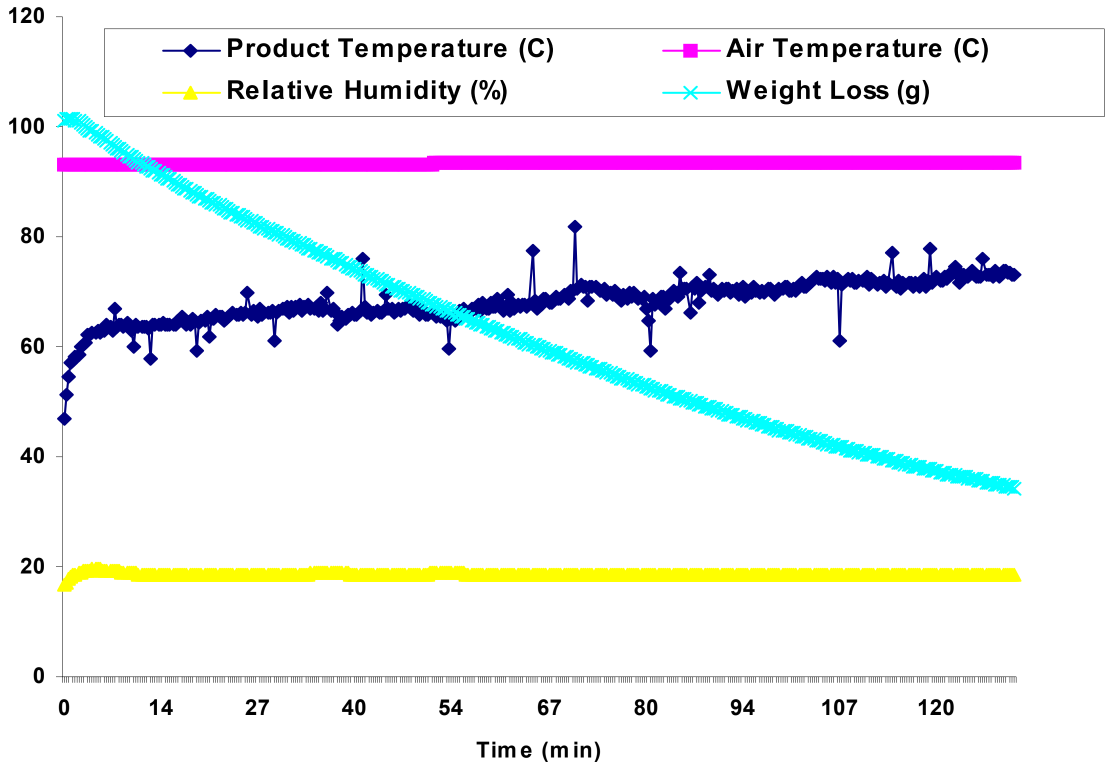

Figure A9 Convection drying (weight loss, g) of untreated saskatoon berries at 70^{0}C temperature

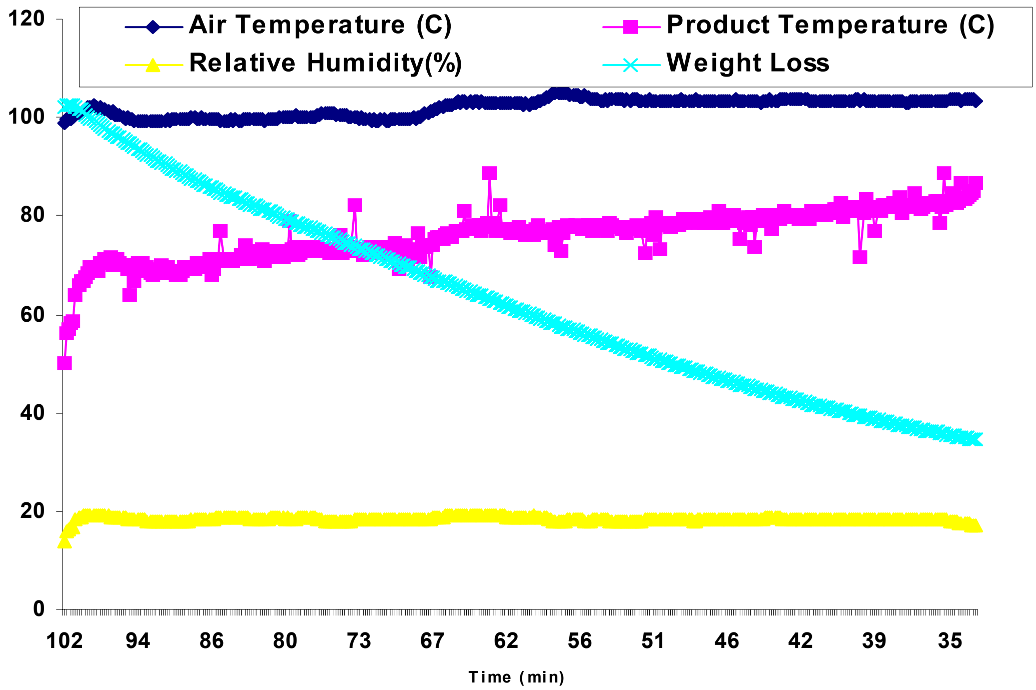

Figure A10 Convection drying (weight loss, g) of untreated saskatoon berries at 80^{0}C temperature

Appendix A4. Temperature trends during microwave drying at 60°C.

Temperature variation at microwave power level P1 (refer Table 4.1) with time at different locations of the sample holder.

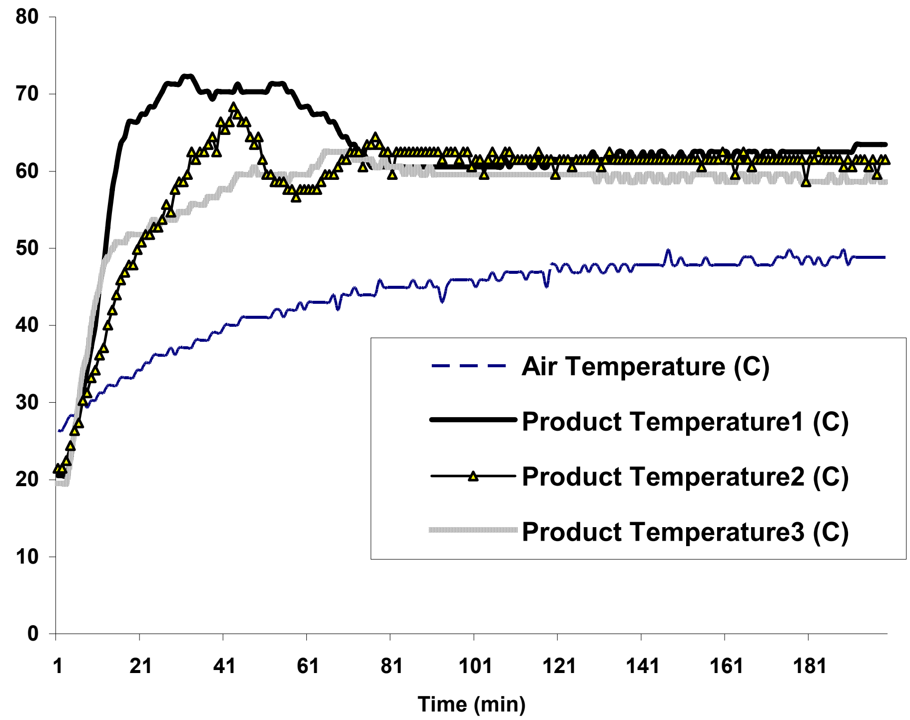

Figure A11 Microwave drying product temperatures of high fructose corn syrup treated saskatoon berries at 60^{0}C product temperature and corresponding air temperature (^{o}C) plotted against time (min)

Note: Product temperatures are at three different locations on the sample holder.

Appendix B1. Microwave drying of fresh blueberries

Fresh blueberries in microwave environment and rupture due to high power treatment.

Figure B1 Blueberries disintegrated structure after low power microwave drying

Appendix C1. Dielectric properties of saskatoon berries

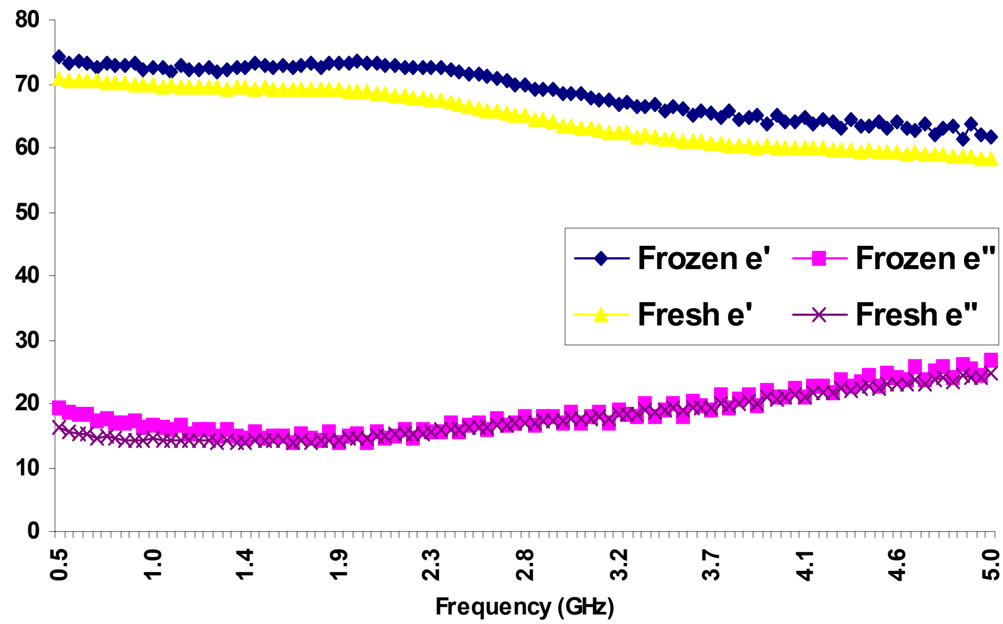

Figure C1 Dielectric properties of frozen saskatoon berry syrup

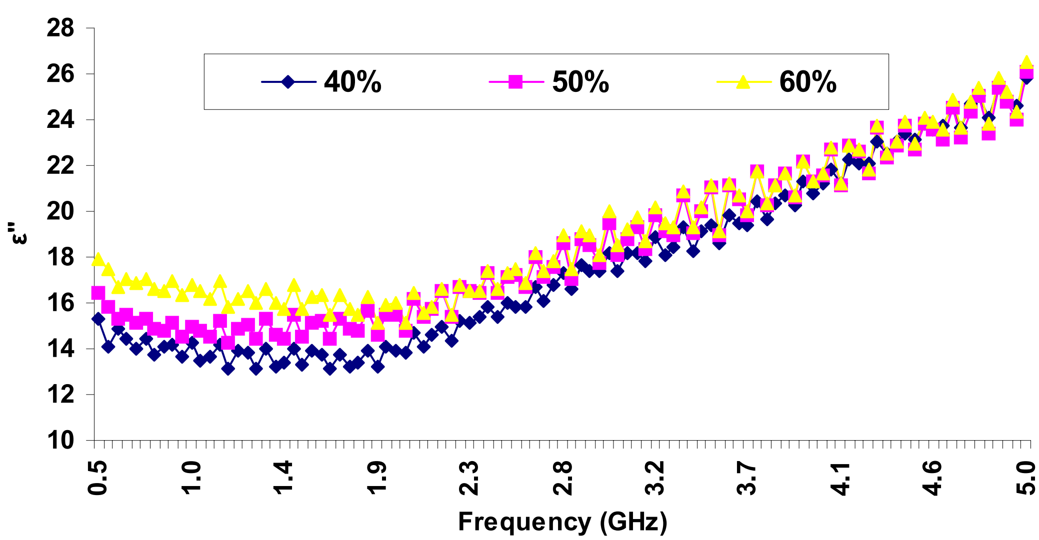

Figure C2 Dielectric loss factor variation of saskatoon berry syrup after osmotic dehydration with 40, 50 and 60% sucrose sugars solutions

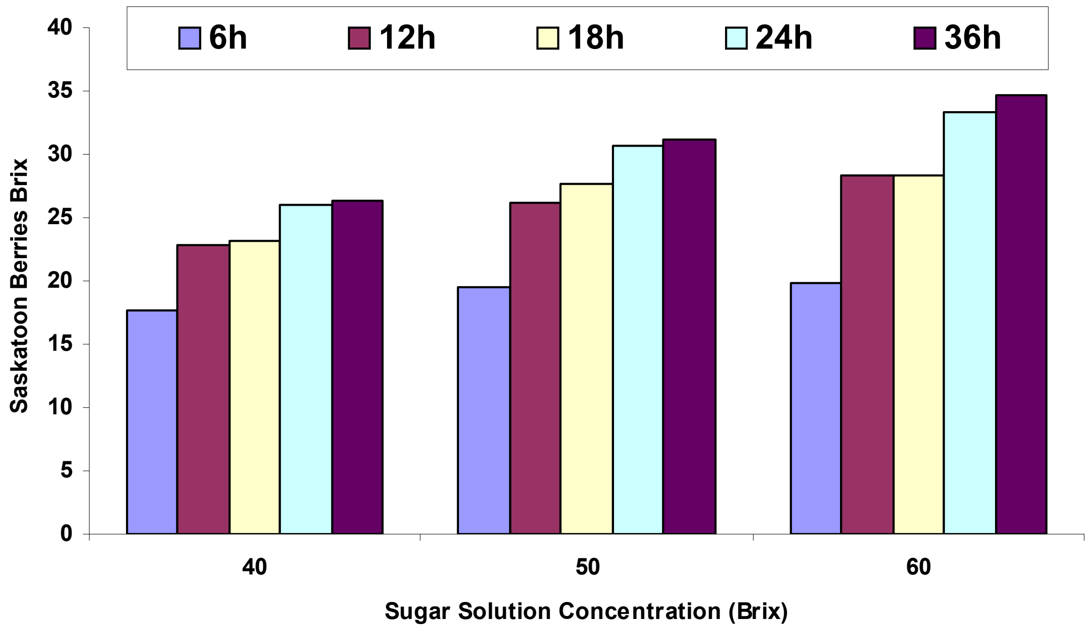

Figure C.3 Effect of high fructose corn syrup Concentration on Osmotic Dehydration

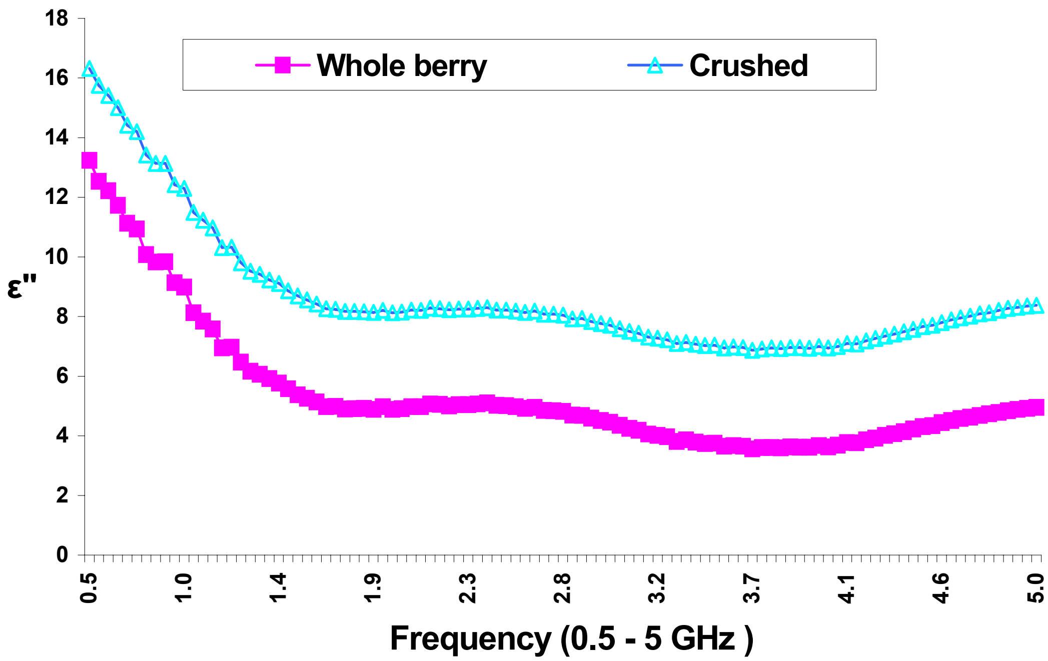

Figure C4 Dielectric loss factor (ε") variation with frequency of Fresh saskatoon berries

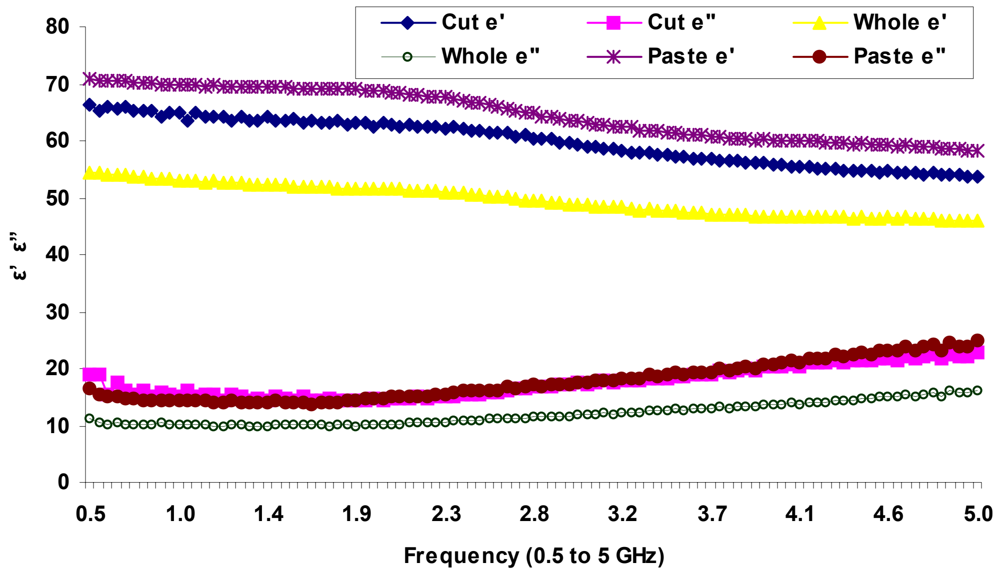

Figure C5 Dielectric properties of fresh whole, cut and syrup of berries

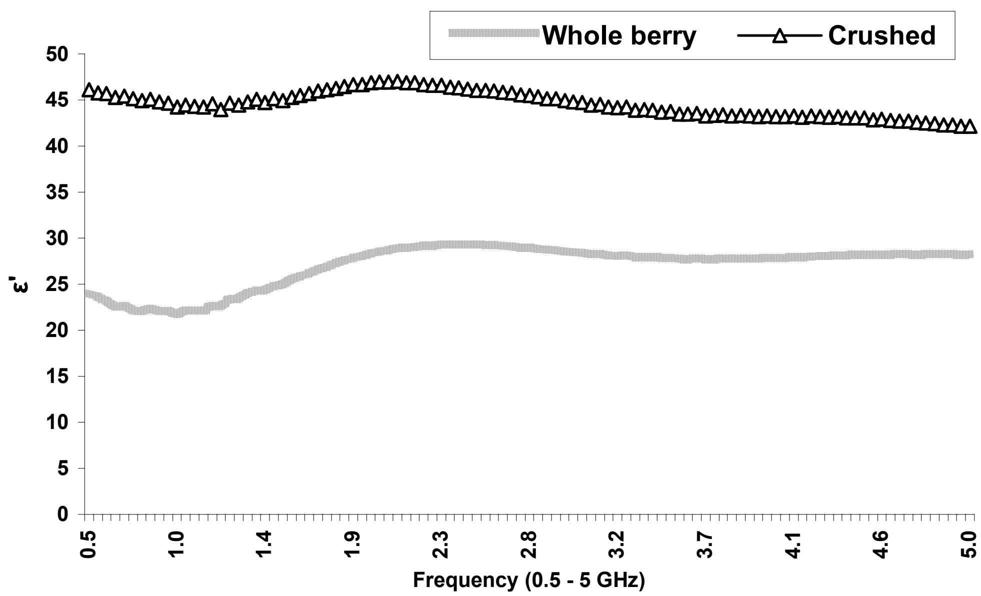

Figure C6 Dielectric constant (ε') variation with frequency of frozen saskatoon berries (whole and crushed)

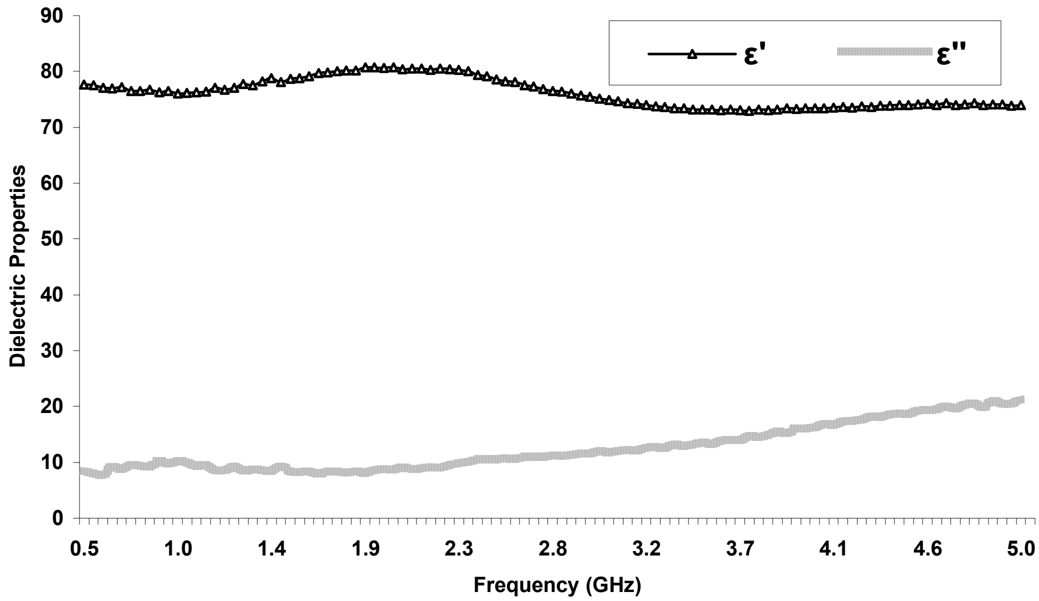

Figure C7 Dielectric constant and Loss factor variation with frequency of water

Appendix D1. Scanning Electron Microscope images of saskatoon berries

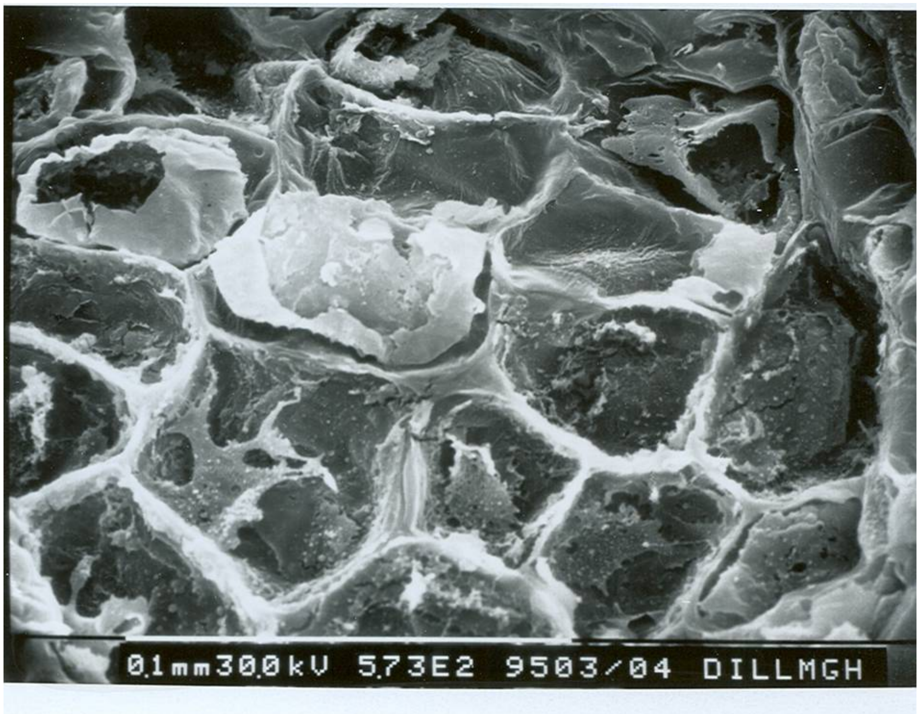

Figure D1 Scanning electron microscope image of osmotically dehydrated berries with 50% sucrose solution

Appendix E1. Digital Images of Experimental Setup

Figure E1 Frozen saskatoon berries

Figure E2 Thawed saskatoon berries placed in polycarbonate sample holder.

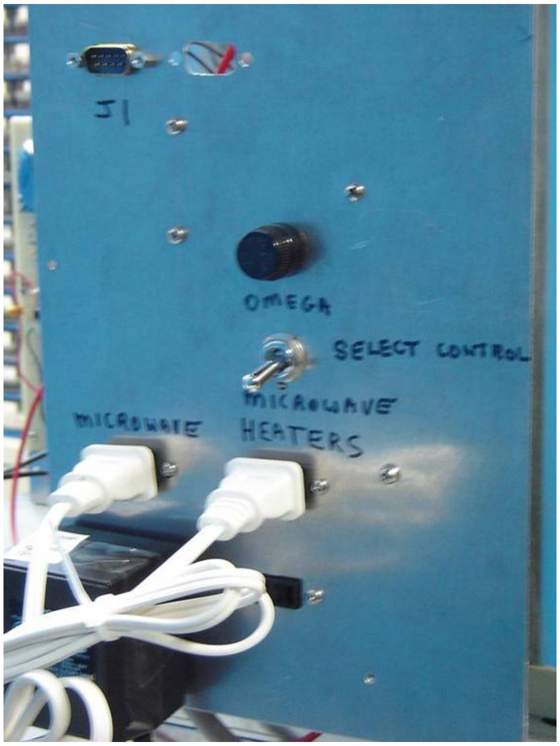

Figure E3 Panel to switch between preset and modified settings

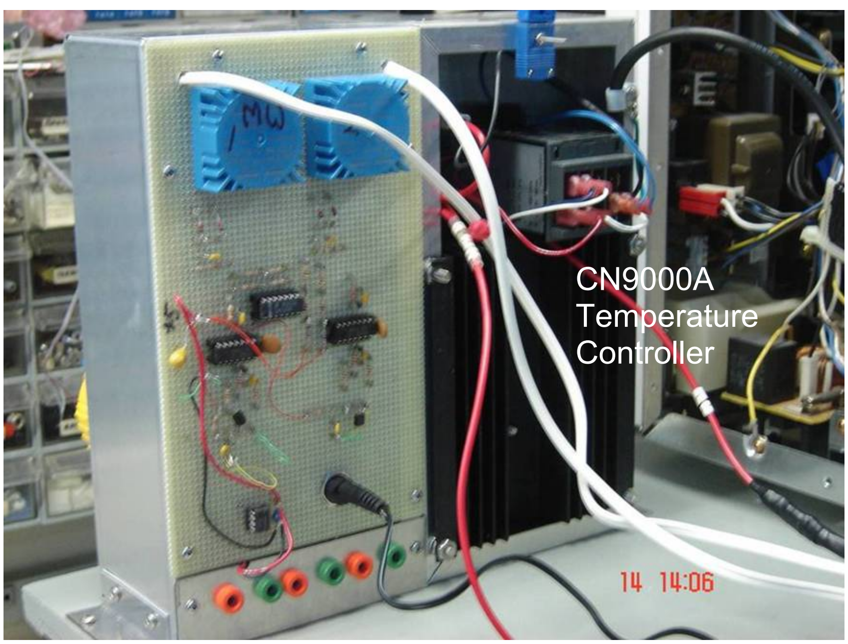

Figure E4 Front panel with temperature controller and setup to monitor convection and microwave run-time

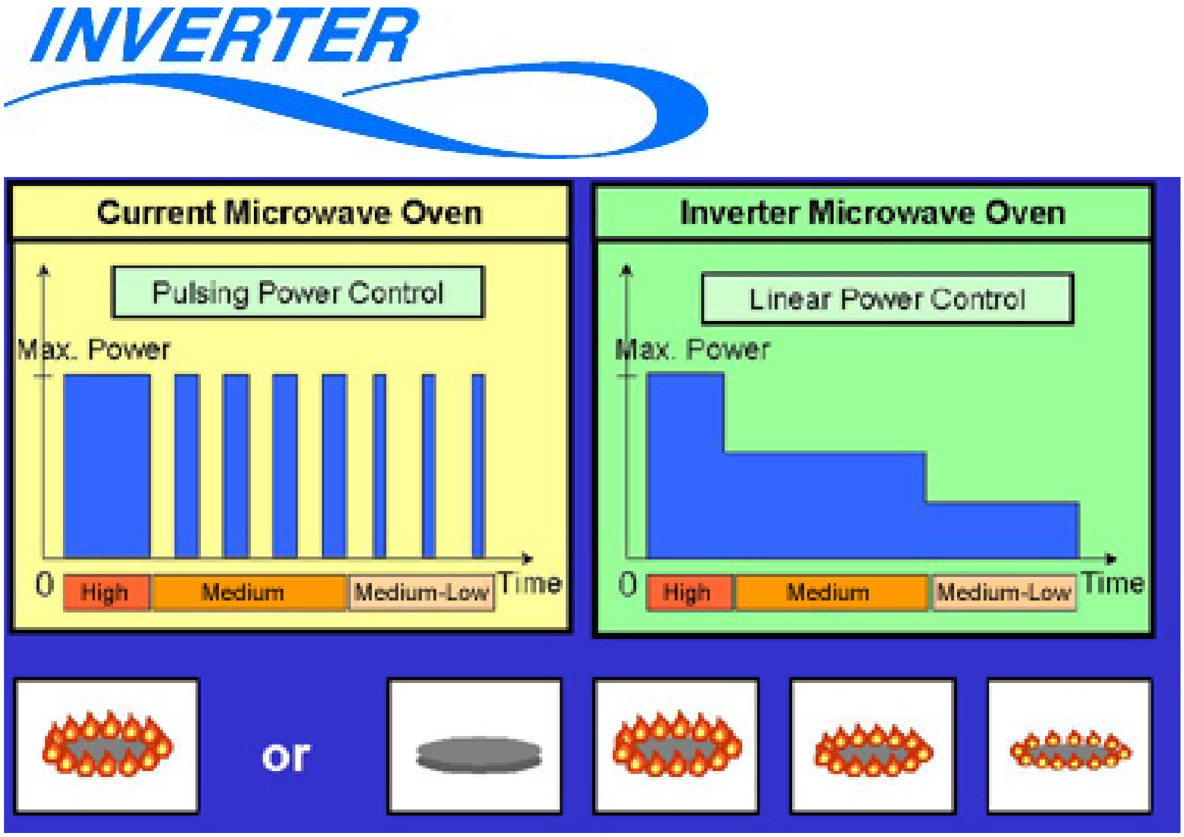

Figure E5 Inverter technology built in the Panasonic microwave-convection system